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"The role of thermal mass materials in net-zero energy buildings"

Thomas Zandes

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SCHOOL OF SCIENCE & TECHNOLOGY

A thesis submitted for the degree of

Master of Science (MSc) in Energy Systems

DECEMBER 2013

THESSALONIKI – GREECE

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Abstract

According to the recast of the European Performance of Buildings Directive (EPBD) all new buildings that will be built from 2021 and on, should be nearly zero energy buildings. The majority of buildings in Greece are heavyweight constructions that contain high amount of thermal mass. The relation and the integration of thermal mass materials with the entire NZEB performance were investigated in this dissertation. The first part of this dissertation presents a comparative evaluation and selection of thermal mass materials for periodic energy storage in buildings. A selection of materials using a selection strategy which includes a filtering process was implemented. During the selection process 127 different materials both conventional and unconventional were checked. An attempt to discover new alternative materials suitable for effective thermal energy storage was also made. Three materials stood out through the filtering process. Limestone, lightweight concrete and autoclaved aerated concrete. In the second part of the dissertation a dynamic thermal simulation of the selected materials the climatic conditions of the four climatic zones of Greece, was implemented. The thermal performance of walls constructed from the above materials was compared with the performance of common brick walls. Finally, the use of thermal mass for energy storage in order to overcome the mismatch barrier between supply and demand in a NZEB by implementing a simple pre-cooling strategy during the summer months was also investigated.

Thomas C. Zandes

December 2013

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1 Introduction

1.1 Sustainability and the building sector

The impacts of climate change and global warming are already obvious and have already begun to alter life on the planet. Therefore, now more than ever, the need to radically change the way of producing and using energy is urgent, in order to effectively face climate change and its adverse effects. The new approach that has been recently introduced is based on sustainable development and it aims to improve humanity's relationship with the living world and to improve our life quality.

Buildings have direct impact to the environment, through the use of raw materials, the consumption of natural resources and the production of pollutants and household wastes. During the last thirty years many changes have taken place in the building sector towards the construction of more environmentally responsible buildings.

The zero energy buildings approach represents a change in the way we understand, design and construct today. Zero energy buildings offer an exciting vision for the future, a vision that attempts to redefine the architecture principles and directions, rediscovering the passive design of the past and integrating renewable energy systems to provide solutions that set new standards for building and occupant performance.

1.2 Net Zero Energy Buildings

1.2.1 Defining Net Zero Energy Buildings

The idea for the zero energy building resulted from the need to reduce energy consumption and CO_2 emissions in the building sector and the perception that buildings can cover their energy needs by renewable resources.

Despite the common use of the term "Zero Energy Building", a widely acceptable definition does not exists. It still remains a complex concept with numerous existing approaches and definitions. The most common term that is used is the Net Zero Energy Building (NZEB). A Net Zero Energy Building (NZEB) is a building that has zero net energy consumption and zero carbon emissions over the period of one year. The concept *zero energy* does not mean that the building uses no energy. It refers to reaching a net zero energy position by producing energy from renewable energy systems (Figure1.1). Net zero energy is an operational goal. The period for measuring performance is one year of operation, to include all seasonal variations. Thus, it is not enough only to design a net zero energy building, but it is a requisite to operate like one [Hootman(2012), Voss and Musall (2011), Kosmopoulos and Papakostas (2012), Marszal et al.(2010)].

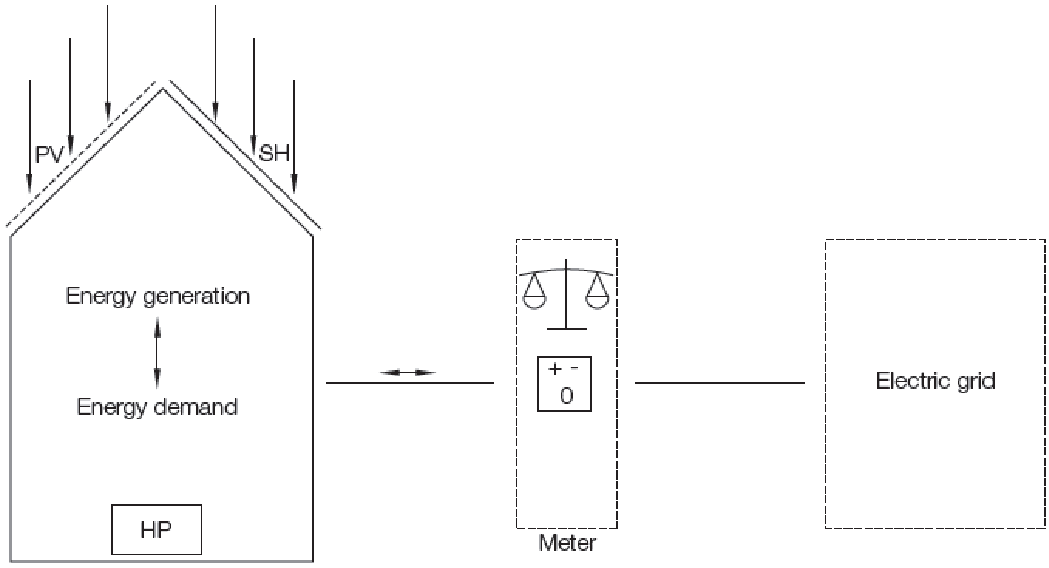

Figure 1.1: Schematic representation of a typical on-site NZEB [Voss and Mussall 2012]

In order to define a building as NZEB, the National Renewable Energy Laboratory (NREL) [Torcellini et al. 2006] in US has proposed four different definitions (see Figure 1.2). There is no issue of comparison between them and each one could be used according to the targets that the designer wishes to achieve.

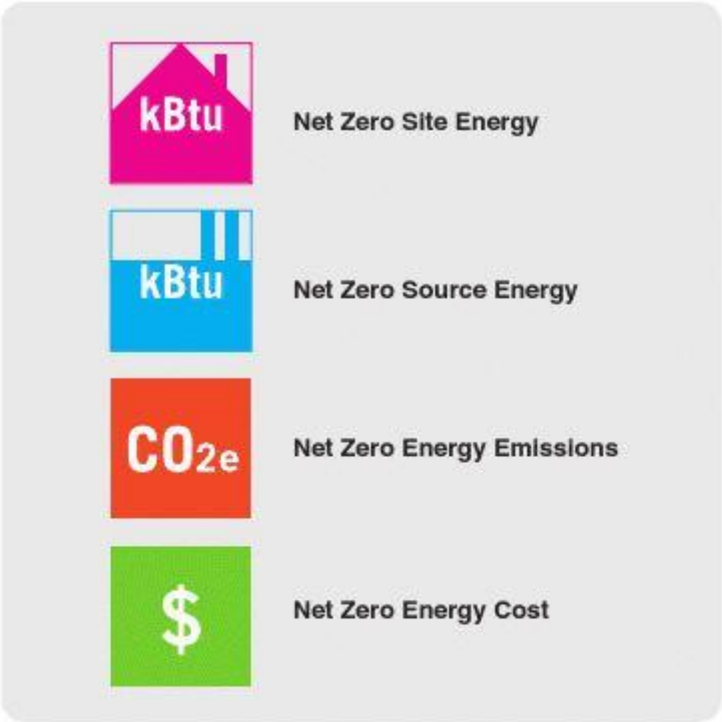

Figure.1.2: Net Zero Energy Building definitions [Hootman 2012]

- **Net Zero Site Energy:** The building produces from renewables provided by on-site, at least as much energy as it uses in a year.
- **Net Zero Source Energy:** The building produces or purchases at least as much renewable energy as it uses in a year, when accounted for at the source. Source energy refers to the primary energy used to generate and deliver the energy to the site. To calculate a building’s total source energy, imported and exported energy is multiplied by the appropriate site-to-source conversion multipliers.
- **Net Zero Energy Costs:** In a cost NZEB, the amount of money that the utility pays to the building owner for the renewable energy that the building exports to the grid, is at least equal, to the amount the owner pays the utility for the energy services and energy used over the year.
- **Net Zero Energy Emissions:** A net zero emissions building produces or purchases at least as much emissions-free renewable energy as it uses from emissions-producing energy sources.

1.2.2 Classification of Net Zero Energy Buildings

Apart from the definition, a NZEB can be categorized based on the RES that are used to meet its energy demand. This categorization urges the designers and the owners of NZEB to use already available and local on-site RES supply solutions rather than remote and more grid burdening off-site solutions. Under this classification system the NZEB is divided into four categories: A, B, C and D. The classification is proposed again by NREL [Torcellini and Pless 2009] and is summarized in Table 1.1.

Table 1.1: Net Zero Energy Classification System [Torcellini and Pless 2009]

Net Zero Energy Classification System		
On Site RES supply	Class A	Use RES available within the building's footprint and directly connected to the building's electrical system or DHW distribution system. Examples: Roof PV systems, solar water heaters etc.
	Class B	Use RES as described in Class A but also use RES available at the building site (not physically mounted on the building) and directly connected to the building's electrical or DHW distribution system. Examples: nearby PV or wind parks etc.
Off Site RES supply	Class C	Same as Class A,B but also use RES available off site to generate energy on site and directly connected to the building's electrical or DHW distribution system. Examples: biomass, wood pellets, ethanol, or biodiesel that can be imported from offsite, or collected from waste streams from on-site processes that can be used on-site to generate electricity and heat.
	Class D	Same as Class A,B,C but also purchase extra off-site RES, as certified from Green-E (2009) or other equivalent renewable-energy certification programs. Continue to purchase the generation from this new resource to maintain NZEB status. Examples: Utility-based wind, photovoltaic, emissions credits, or other "green" purchasing certified options.

Generally, there is no optimal definition or an optimal class for NZEB, as well as there is not yet a standard definition and a single standardized methodology for monitoring and building a NZEB. The definition or the class that is usually depends on the goals set by the designing team or the building owner. For example, the owners are mainly interested in the payback period of the cost of operation and construction, and environmentally conscious businesses are interested in the control of their emissions.

Regardless of any definition or classification, a NZEB is first and foremost, an extremely low-energy building. This is a very important general rule. Designers and occupants of a NZEB should firstly make use of all the available methods and technologies to achieve maximum energy efficiency of the building, and then apply the RES technologies giving priority to the use of those that are available very close to the building, or on the building itself. By this way the costs and losses resulting from the transfer and energy conversion are minimized.

1.2.3 EU policy goals

The NZEB concept is of great interest in the EU. The building sector is responsible for 37% of the total energy consumption in EU [Eurostat 2012], therefore it becomes clear why EU environmental policies focus on this sector. It seems that goals are easier to achieve here than on any other sector. Besides, in many European countries, zero energy buildings are considered to be the evolution from low-energy houses towards passive houses.

The recast of the European Performance of Buildings Directive (EPBD) [Directive 2010/31/EU (recast)] in 2010 introduces a new term "*nearly Zero Energy Building*" (nZEB) and specifies timeframes for the implementation of related construction standards within its member states:

- *"Article 2(2): Definitions:*

  Nearly zero-energy building means a building that has a very high energy performance …. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby.

- *Article 9: Nearly Zero Energy Buildings: Member States shall ensure that:*

  a) by 31 December 2020, all new buildings are nearly zero-energy buildings; and

  b) after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings. Member States shall draw up national plans for increasing the number of nearly zero-energy buildings. These *national plans may include targets differentiated according to the category of building."*

The recast of the European Performance of Buildings Directive (EPBD) requires all new buildings to be "nearly zero energy" buildings (nZEB) by 2020, including existing buildings undergoing major renovations. As usual in such strategy directives, interpreting the implementation of measures and methods of calculation are left to member states. How close the "nearly zero" approach is to the "zero" approach, still needs to be clarified.

The draft of the directive still contained the phrase "zero energy buildings", but this was obviously considered too ambitious as a goal [Voss and Musall 2011]. The need for a clear calculation methodology has gained attention with the growing number of NZEB projects and thus the interest in how the 'zero' balance is finally calculated. Some countries are on their way to include the NZEBs in their national building codes, however no standardized calculation procedure yet exists and most of the calculations are just voluntary proposals developed for a particular NZEB case.

While other methodologies like the passive house standard are defined by a method of calculation, the concept of a "near zero energy building" lacks authority, while further procedures are open to interpretation by each respective nation. Despite numerous efforts to streamline construction standards internationally, we are still in the beginning of any effective effort.

1.3 Mismatch between production and demand in NZEB

Because of the fact that a NZEB uses intermittent and often not available for long periods renewable energy sources (such as solar and wind) this will inevitably lead to a mismatch barrier between on-site renewable energy production and the local building demand. The mismatch is both seasonal and diurnal.

For example a residential building, equipped with solar heating or solar electricity generation, has a demand that is at its peak in the winter while on-site supply is at its lowest, and vice versa in the summer. Likewise the peak of the solar supply occurs during the day when the heating demand is low, and the highest demand usually occurs at the evening or early in the morning, when sun irradiation is low [Widén et al. 2009].

Because of these natural reasons, there is a need for a system able to produce such a time delay to the phenomenon, that the energy supply can meet demand at any time. With *energy storage*, the NZEB can overcome the mismatch barrier. For most of the NZEB that are grid-connected, the grid itself is used as a virtual storage [Reynders et al. 2013]. When the generation of energy on-site, exceeds the building's demand, the surplus is fed into the grid and vice versa. However, with an increasing number of renewables that are gradually entering the grid, this extra load may stress local distribution grid and lead to grid instability and decreasing efficiencies of large power plants.

The need of energy storage in the form of thermal energy storage (TES) is the simplest and least expensive way to store energy [Garg et al. 1985]. One of the most widely used techniques for thermal energy storage is the sensible heat storage method. This thesis it will be focused in this kind of energy storage technique. Other energy storage techniques that will be further analyzed in the following chapters, such as latent heat storage and thermo-chemical heat storage appear to be promising, however currently most of them are still in an experimental stage.

The period of storage is divided in two main categories:

- Short term storage
- Long term storage.

With short term storage the energy is stored for a few hours usually for diurnal storage cycles, while with long term storage the energy is stored for months usually for seasonal cycles. In this thesis short term periodic thermal energy storage for on-site building use will be analyzed, as long term storage techniques are usually based on off-site district heat systems.

The building structure itself can be used as a medium for thermal energy storage. The *thermal mass* of the building can be used as a heat sink and a modulator of internal temperature that could lead to energy consumption management. With the utilization of thermal mass the buildings can moderate the mismatch of supply and demand, by storing the generated surplus of energy and use it later when the demand is higher.

In order to efficiently implement any kind of energy storage method that has been already mentioned the choice of the storage material is important. A material with high heat storage capacity and good heat transfer characteristics will improve the performance of the heat storage system. Some other material parameters such as cost, environmental impacts, and safety conditions, also play an important role and therefore should be taken into account during the design of NZEB [Tatsidjodoung et al. 2012].

1.4 Subject of the Thesis

This thesis aims at presenting a comparative evaluation and selection of thermal mass materials suitable for periodic energy storage in buildings. It also has a goal to discover new alternative materials suitable for effective thermal energy storage. The relation and the integration of thermal mass materials with the entire NZEB performance is one of the issues that will be investigated. Moreover, this thesis aims at performing an efficient comparison, in terms of energy storage and energy savings potential, of the selected materials with the most common that materials are used currently in buildings. Its final goal is to evaluate the potential of using the thermal mass for energy storage, in order to overcome the mismatch barrier between supply and demand in a NZEB.

1.5 Structure of the Thesis

The thesis is divided into three parts:

The first part of the thesis contains the abstract and the contents. The second part which is the main part is consisted of 6 chapters. The third part consists of the bibliography that was studied for the writing of this thesis.

The first chapter presents a review of the definitions, the main characteristics and the classification of Net Zero Energy Buildings. Moreover, it emphasizes to the mismatch barrier between the production and the demand in a NZEB and specifies how the thermal energy storage with the utilization of the building's thermal mass could give solution to the problem.

In chapter two, a literature review of all the papers, articles, etc. that have been studied in order to complete this thesis are presented. The first part refers to the utilization of thermal mass in order to achieve energy savings and thermal comfort in buildings while the second refers to the available materials for thermal energy storage.

In chapter three the properties of thermal mass materials for periodic thermal energy storage were presented. Thermophysical and other properties were combined and plotted together in order to facilitate their classification and comparison.

In chapter four, a selection of materials is implemented by inserting various constraints. An exhaustive selection strategy, which includes an elimination process, will lead to the materials that satisfy all the constraints that were initially posed.

In chapter five a simulation process is implemented, in order to perform an effective comparative evaluation of the selected thermal mass materials of chapter four.

Finally, in chapter six, the most important conclusions of this thesis are presented, as well as some suggestions for further research.

2 Literature review

2.1 Thermal energy storage in building structure

The building structure itself can be used as a medium for thermal energy storage. The thermal mass of the building can be used as a heat sink and a modulator of internal temperature that could lead to energy consumption management. Apart from the use of thermal mass as a heat sink that can absorb both internal heat gains and solar gains, thermal mass can be used to minimize temperature fluctuations during the summer.

The advantages of heavy structured buildings that can exploit the thermal inertia were known from ancient years. Massive walls absorbed the unwanted heat during the day, reducing the internal temperature and improving thermal comfort. This technique was widespread in the region of the Mediterranean and constitutes the cornerstone of traditional architecture. In this region the climate is moderate often combined with high diurnal temperature swings.

Researchers wondered if the utilization of thermal mass could be effective to modern buildings in climates outside Mediterranean region. Goodwin and Catani (1979), investigated the effect of building's mass on heating and cooling demand, in different climates. Walsh et al. (1982), tried to simulate, using computer software for the first time, the performance of both heavy and light buildings in Australia. Snyder and Newell (1990), developed a method to determine the least-cost cooling strategy for a building by using the building mass for thermal storage. The basic concept was to use air conditioning system to pre-cool the building during off-peak hours when the demand for electricity is low. Ruud et al. (1990), performed an experiment in a large office building in Florida. The building was pre-cooled at night and during the weekend and reducing by this way the cooling demand by 18% . Balaras (1996), concluded that high thermal mass buildings have smaller temperature swings than low thermal mass buildings and they can lead to significant reduction in energy demand for cooling particularly in locations with high diurnal temperature swings. Givoni (1998), compared two buildings in Southern California with similar U values but different percentage of thermal mass. He found that the heaviest building achieved 3- 4.5^{o}C temperature reduction. Ogoli (2003), concluded also that thermal mass reduces indoor temperature fluctuations in his tests performed in Kenya. Al-Sanea et al. (2011), confirmed all the previous claims by Ruud, Balaras, Givoni and Ogoli for lowering cooling demand and lower indoor temperature fluctuations. Furthermore, he highlighted that exploiting thermal mass, could lead to lower heating demand in locations with high diurnal temperature swings. He calculated the performance of a building located in Riyadh, by keeping all other factors constant and modifying the amount and the location of thermal mass. He found that maximum savings in yearly transmission loads were 17% for cooling and 35% for heating. However, Zhu (2008), studying the performance of two identical zero energy houses in the dessert of Las Vegas, one with low thermal mass levels and the other with high, found that cooling loads in the high mass house were increased in relation to the low mass house. Apart from that he reported that the high mass building had much lower heating energy demand and more stable indoor temperature. Kalogirou et al. (2002), performed an energy consumption analysis in a building located in Cyprus, using TRNSYS simulation software. The building's south wall was replaced by a thermal wall and the results showed a reduction of heating load by 47%, while at the same time the demand for cooling was slightly increased.

Despite the encouraging results of the utilization of thermal mass in moderate and hot climates or in climates with high diurnal temperature swings, studies made for Northern climates showed that thermal mass has little contribution to energy savings. In the Scandinavian region lightweight wood frame buildings of low thermal mass are a very common way of construction. Noren et al. (1999), concluded that the effect of thermal mass in Swedish buildings is low. Jokisalo and Kurnitski (2005), reported that heating energy savings in Finnish houses were between 0.7- 2%. Similar results (0.5-2.4%) demonstrated by Dodoo et al. (2012), for Swedish houses. However, Kalema et al. (2008), using different simulation programs found that the utilization of thermal mass in Scandinavian buildings could lead to 4-16% reduction ~~for~~ of heating demand.

Although thermal mass can lead to lower energy consumption, there have been some studies that showed the opposite. Bloomfield and Fisk (1977), studied office buildings with intermittent occupancy and concluded that thermal mass does not help to lower heating demand. The CIBSE Guide F (2004), reported that buildings with high thermal mass under intermittent heating, consume more heating energy than low thermal mass buildings. Tuohy et al. (2004), performed several tests using both high and low thermal mass buildings and found out that those with high mass can under circumstances consume more heating energy. Actually, Tuohy in his study specified when the effect of higher energy consumption is possible to occur. He used a simulation of two simple rooms, one with low thermal mass materials and the other with high thermal mass materials and studied their performance at climatic conditions of Jersey (UK) and Copenhagen, while he adjusted the amount of insulation. The results showed that the high mass model could consume more, similar or less heating energy, depending on the three levels of insulation. When the insulation level was high, the heavier mass model consumed less energy. If the level of insulation is low, more energy will be consumed in order to heat the building structure but eventually a significant part of it, will be wasted as it will leak out to the environment. The combination of cold climate, weekend occupancy and low insulation levels can increase the demand for heating significantly.

Obviously the occupancy pattern plays an important role for the utilization of thermal mass. In buildings with high intermittent occupancy perhaps there is no need to exploit the thermal mass of the building structure. Various studies made from Bojic (1981), Kossecka and Kosny (1998), Al-Sanea and Zedan (2001),Tsilingiris (2006), showed that placing the insulation in the internal side of the building can lead to lower energy consumption and higher thermal comfort.

In most cases, the researchers tend to agree that placing the insulation on the outer side of the building is more advantageous as it gives the opportunity to exploit the benefits of the thermal mass and this applies in all climates. Recently researchers inquired of the effective amount of thermal mass that should be placed into the buildings. Ma and Wang (2012), investigated the optimal thermal mass thickness of indoor building materials subject to sinusoidal heating and cooling loads using dynamic heat transfer model of interior Planar Thermal Mass (iPTM). They concluded that the heat storage capacity of the materials reaches its maximum value at an optimal thickness. Building elements with higher thicknesses than optimal will not store any further energy and thus they will not utilize their thermal mass. Stahl (2009), using the periodic penetration depth simplified model, reports that the optimal thickness of a building’s element is close to periodic penetration depth and nothing is gained in terms of energy storage by increasing it. Stahl also reports that the total area of a building’s structure that is in contact with the inner heated or cooled space plays important role, as it is proportional to the energy storage capacity.

Shao (2010), underlines that “as with many other technologies, the high thermal mass design could introduce conflicting design requirements for winter heating and summer cooling and require ‘joined-up’ thinking”. It is a fact that the effectiveness of thermal mass depends on multiple factors such as occupancy patterns, climatic conditions, insulation, ventilation, air-tightness etc. The proper design of a building must take into consideration all the aforementioned factors and should be based on detailed modelling of the building, rather than copying.

2.2 Materials for thermal energy storage

The research activities in the field of Thermal Energy Storage (TES) intensified at early seventies and continued until nowadays with increasing interest in various research centres in many countries. Nevertheless, there is a feeling amongst the researchers that one of the weakest points of this technology is the materials that are used as storage medium. The same materials that have been evaluated as potential materials for thermal energy storage are the materials studied today [Fernandez et al. (2010)].

Most of the research that has been made refers to latent heat materials commonly known as phase change materials (PCMs).A total evaluation of potential materials for thermal energy storage conducted by Lane (1983; 1986). Numerous recent works in the same field presented by Zalba et al. (2003), Dincer and Rosen (2002) and Mehling and Cabeza, (2008), pointed out the same materials with Lane. These materials are parafinns, fatty acids and salt hydrates for latent heat storage and molten salts for sensible heat storage.

Tatsidjodoung et al. (2013), presented all the potential available materials for thermal energy storage in building applications. The study includes sensible, latent and thermo-chemical heat materials emphasizing in their thermophysical properties.

Thermo-chemical heat materials are very popular in recent studies for thermal energy storage, although the research is still in early stage. Cot-Gores et al. (2012), summarizes the work that has been made in this field in the last twenty years. Common materials being under research are silica aerogels, zeolites, LiBr ,LiCl etc.

Ashby (2005) and Ashby et al. (2007), developed a software able to perform selection of materials inserting a number of different parameters. The software called *Cambridge Educational Software (CES) Selector* and is commercial software created by Granta Design, in partnership with the University of Cambridge [www.grantadesign.com]. With the methodology introduced by Ashby researchers can select, classify and evaluate materials not only considering their thermophysical properties, but also by adding different inputs like cost, mechanical behavior, recyclability, CO_2 footprint etc.

Using CES selector researchers attempted a selection and evaluation of sensible heat materials, which is a field that was supplanted by the research in latent and thermo-chemical heat materials. A basic motive under this revulsion was the need for low-cost materials because of the global recession. Fernandez et al. (2010), using CES selector, searched for potential materials for sensible energy storage in temperature range of 150-200^{o}C with the objective of minimizing cost and found out that, halite, lightweight and asphalt concrete perform well for both long term and for short term storage. Navaro et al. (2011), using the same software, evaluated the potential of recycled materials for sensible thermal energy storage. WDF which is a powder produced in steelmaking process, IB and WrutF which are by-products of the mineral industry, showed the greater performance. Cofalite, which is a recycled ceramic made of vitrified asbestos containing wastes, performed also quite well.

The most recent research using CES software was conducted by Jeanjean et al. (2013). The research defines the selection criteria of thermal mass materials for low-energy building construction. It includes a comparison and evaluation of both conventional and alternative materials for sensible energy storage into the building's structure. Although the main quest of this work was to evaluate the performance of Cofalite as a building material, many other interesting results emerged. Limestone a material known for its positive inertial properties since ancient years had an excellent performance in almost every test. Together with concrete and terracotta these materials are the most advantageous thermal mass materials, combining high thermal storage capacity with low embodied energy and low cost.

Kurkinen and Karlsson (2012) and Karlsson (2012) studied whether it is possible to improve the thermal properties of the concrete for buildings. The basic idea was the addition of aggregates with high heat capacity and/ or aggregates with high thermal conductivity. They used eleven different concretes containing magnetite, graphite, copper, brass and PCMs .It was found that both volumetric heat capacity and thermal conductivity can be increased by at least 50% compared to standard concrete.

3 Materials for energy storage in buildings

3.1 Thermal Energy Storage

Thermal Energy Storage (TES) is the storage of heat that can be extracted and used at a later time. Like every energy storage process, TES consists of three basic steps:

- Charging (loading),
- Storing
- Discharging (releasing).

In order to store energy we need an energy storage system or a material that is called storage media. In a TES process, heat is transferred to storage media during charging stage and when this period ends, heat is released to be usefully applied. The selection of a storage media depends on several characteristics and requirements such as the storage mechanism, the temperature range and the specific application. In terms of storage mechanism there are three ways to store heat (Figure 3.1).

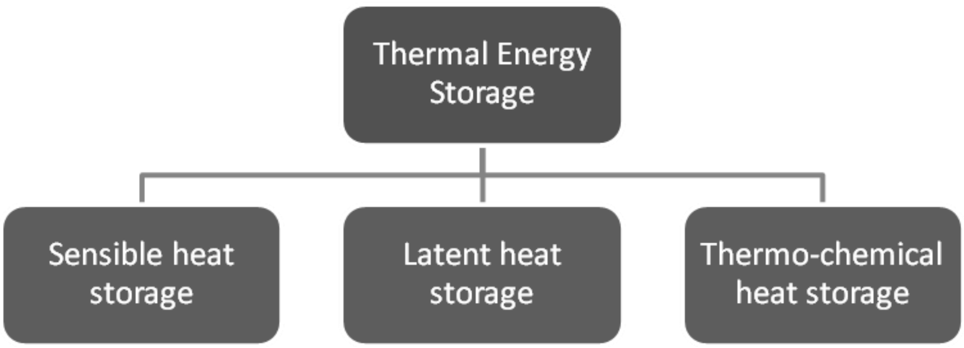

Figure 3.1: TES mechanisms

3.1.1 Sensible heat storage

According to the sensible heat storage mechanism, heat storage is achieved while the material changes its temperature. When temperature increases, thermal energy is stored to the material (charging), when temperature decreases thermal energy is released (discharging). The material is releasing or absorbing thermal energy according to temperature fluctuations and during this process it does not undergo any phase change. For a material that is facing a temperature change from T_1 to T_2, the amount of stored/released thermal energy (Q) is given by the following equation.

$$Q=\int_{T1}^{T2} mC_p dT= V \int_{T1}^{T2}(C_p\rho)dT$$

Where:

- m : material's mass (Kg)
- C_p : specific heat under steady pressure (J/KgK)
- V: material's volume (m^3)
- ρ: material's density (Kg/m^3)
- dT : temperature difference in K

The ability of a material to store thermal energy under the sensible heat storage principle it depends on the ρC_p value (heat capacity per volume). Therefore, this is the most basic parameter for the ability of a material to store sensible heat. The properties of materials that are used for sensible heat storage compared to air are demonstrated on Table 2.1. Air has a higher specific heat than granite stone, but due to the low density of air and the high density of granite, granite can store over 2000 times as much heat as air. Water with its high specific heat and density is the most commonly used material for sensible heat, combining a number of advantages such as low cost, availability, non-toxicity etc. Other materials commonly used are:

- *Liquids:* Molten salts, Organic liquids, Liquid metals
- *Solids:* Concrete, Rock beds, Ceramics, Metals

Table 2.1: Properties of materials used for sensible heat storage compared with air [Atear 2008]

Material	Density (kg/m^3)	Specific Heat (J/kg.K)	Heat Capacity (J/m^3.K)
Air	1.0035	1204	0.0012
Aluminum	2707	896	2.43
Hitec (Molten salt)	1680	1560	2.62
Engine oil	888	1880	1.67
Brick	1698	840	1.43
Brick magnesia	3000	1130	3.39
Concrete	2240	1130	2.53
Cast iron	900	837	0.75
Pure iron	7897	452	3.57
Calcium chloride	2510	670	1.68
Copper	8954	383	3.43
Earth (wet)	1700	2093	3.56
Earth (dry)	1260	795	1.00
Potassium chloride	1980	670	1.33
Potassium sulfate	2660	920	2.45
Sodium carbonate	510	1090	0.56
Stone, granite	2640	820	2.16
Stone, limestone	2500	900	2.25
Stone, marble	2600	800	2.08
Water	1000	4190	4.19

3.1.2 Latent heat storage

In latent heat storage mechanism, heat storage is achieved while the material undergoes a phase change from one physical state to another. The materials that use this kind of mechanism in order to store thermal energy are called Phase Change Materials (PCMs). PCMs are characterized by high energy storage density and limited temperature swing range. Typically the phase change can occur in the following forms:

- Solid-Solid
- Solid-Liquid
- Solid-Gas
- Liquid- Gas

Practically the last two forms are not in use because of the gas instability and large volume change. The most common PCMs are:

- *Organic PCMs*: Paraffins, Fatty acids, Esters, Alcohols
- *Inorganic PCMs*: Salt hydrates, Metals

For the last four decades an extensive research has been made in order to incorporate PCMs in building structure elements like walls, slabs, ceilings etc. The use of these materials is still on an R&D level while there is an effort to overcome a number of limitations like low thermal conductivities, super-cooling, instable melting etc. It is a fact that despite of numerous studies concerning PCMs, some of their thermophysical properties have not been fully assessed yet. High costs and safety concerns are two other parameters that are halting the widespread use of PCMs.

3.1.3 Thermo-chemical heat storage

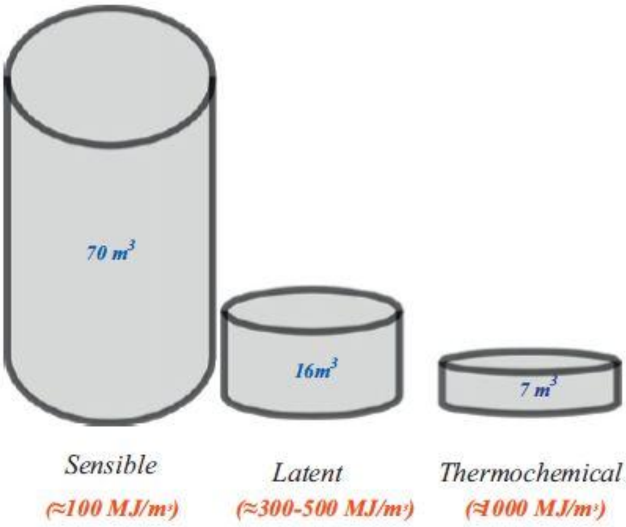

Figure 3.2 : Volume needed to full cover the annual storage need (6480MJ) of an energy efficient passive house [Tatsidjodoung et al. 2012]

During the thermo-chemical storage process, heat can be stored through sorption or due to a combination of endothermic and exothermic reactions that take place in the material. All these reactions are usually reversible. Thermo-chemical storage materials have a formidable storage capacity and negligible heat losses. In 3.2 there is a characteristic example of their storage capacity. The majority of the materials with potential thermo-chemical storage are in R&D level .Common materials being under research are silica aerogels, zeolites, LiBr ,LiCl etc.

3.2 Periodic thermal energy storage in buildings

Buildings consume energy for heating in winter and for cooling in summer in order to ensure thermal comfort. The amount of heating or cooling energy that is required depends on many factors such as the local climate, the season of the year, the time of the day and the user's personal preferences.

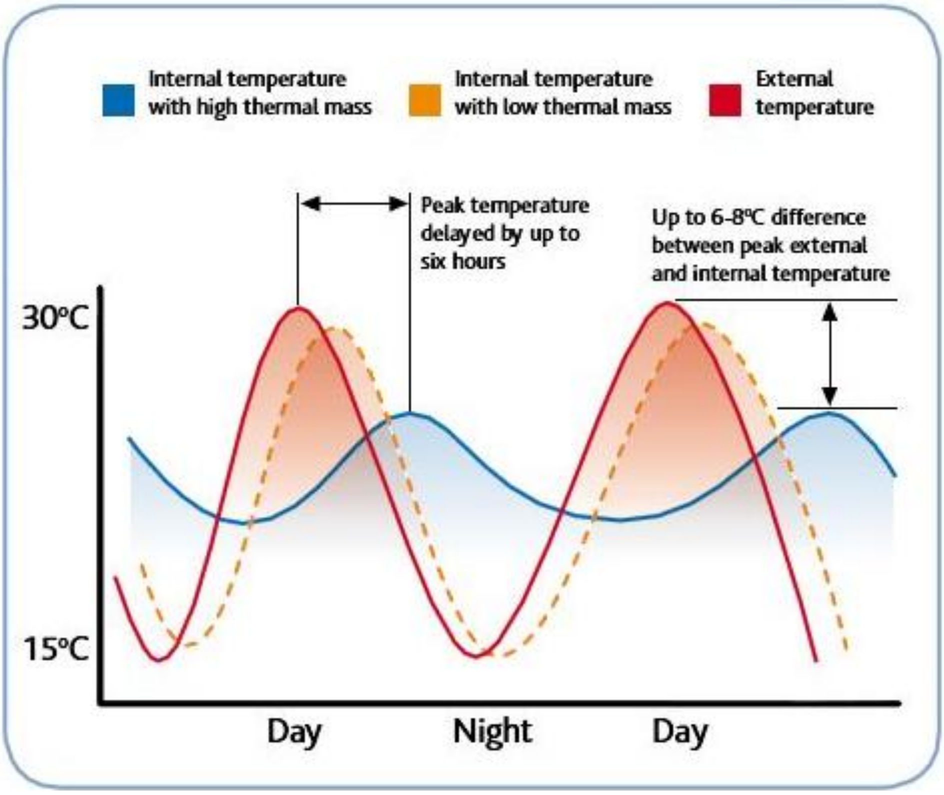

Figure 3.3 : Internal temperature of a high thermal and a low thermal mass building compared with external temperature [de Saulles 2012]

The thermal mass of the building can be used as a heat sink and a buffer of internal temperature that could lead to energy consumption management. It can absorb and store thermal energy surplus when the building's thermal load is high and release it when the load is low. This ability can mediate the diurnal temperature swings, absorbing and storing the excess heat during the morning hours and release it during evening and night (figure 3.3). This process must occur in a time frame that approximates the building's heating and cooling cycle. Therefore, the thermal energy storage of a building occurs periodically

Heat transfer from warm objects to cool objects is achieved by conduction, convention and radiation. In buildings that effectively utilize thermal mass the heat transfer process is a four step process [Haglund and Rathmann 1996]:

- Step 1: Heat is radiated to the surrounding indoor surface of the thermal mass (walls, ceilings, floors) by a warmer object (internal gains or artificial heating from HVAC systems).
- Step 2: Heat is conducted from the warmed surface to the cooler interior of the thermal mass.
- Step 3: When the thermal mass surface becomes warmer than other indoor objects it radiates heat to them.
- Step 4: Heat from the warmer interior is conducted to the cooler surface.

The amount of the surplus heat that can be stored in a building's thermal mass depends, among other things, on the heat storage capacity of the building. The heat capacity of the internal air is by far lower than the heat capacity of the materials of the thermal mass surface. As a result the indoor air temperature changes more quickly than the temperature of the mass surfaces. The difference in temperature will lead to a heat transfer that will reduce the rapid change of the indoor temperature.

The surplus of heat is created due to solar irradiation gains, internal gains (lighting, equipment, people's activity etc.) or by artificial heating from HVAC systems. The indoor temperature rises due to the surplus of heat and eventually the temperature of the building structure will also rise (Figure 3.4a). During the night hours the surplus of heat will be less and the indoor temperature will decrease. However, the stored heat in the building's thermal mass will be released to the indoor air and will prevent the air temperature from plummeting (Figure 3.4b).

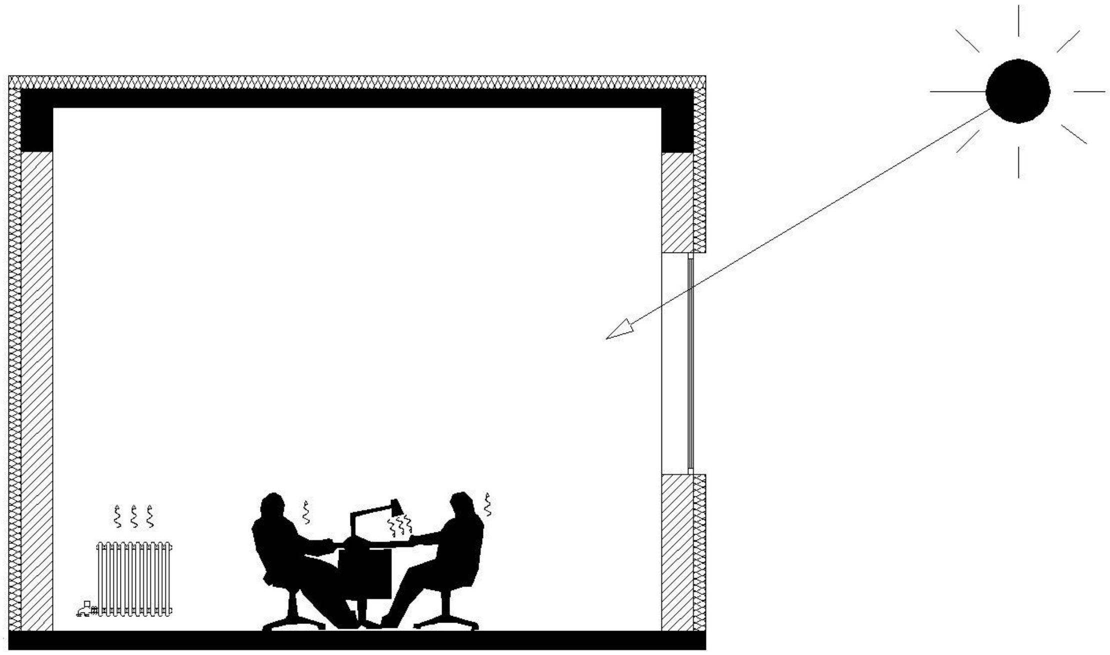

Figure 3.4a : Heat gains during the morning and noun hours

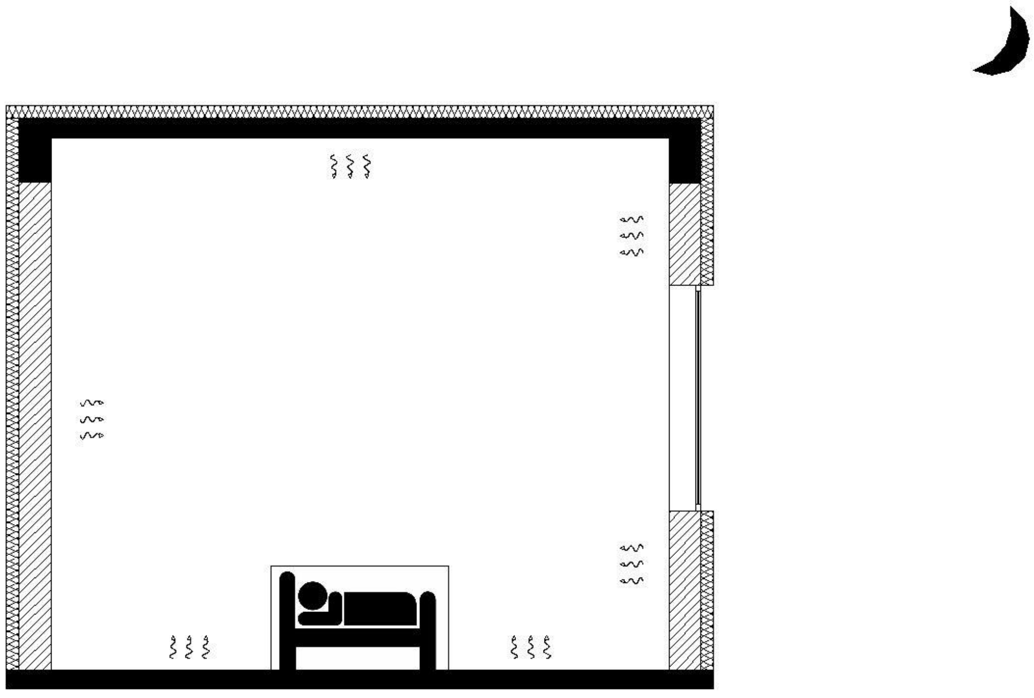

Figure 3.4b : Release of heat during afternoon and night

3.3 Properties of thermal mass materials for periodic thermal energy storage

3.3.1 Storage capacity

As it was mentioned in the previous section, the ability of a material to store thermal energy under the sensible heat storage principle, it depends on the ρC_p value (heat capacity per volume). For building components the term of thermal mass has prevailed in order to describe the ability of thermal storage. Normally all of the building's components, including building materials and internal objects like furniture, participate in the building's thermal mass. However, not all of these components contribute equally to the energy storage. A material that is able to utilize thermal mass effectively, should combine three basic thermal properties (Figure 3.5):

1. High specific heat $\mathbf{C_p}$ (J/kg.K)
2. High density $\boldsymbol{\rho}$ (kg/m^3)
3. Moderate thermal conductivity $\boldsymbol{\lambda}$ or **k** (W/m.K)

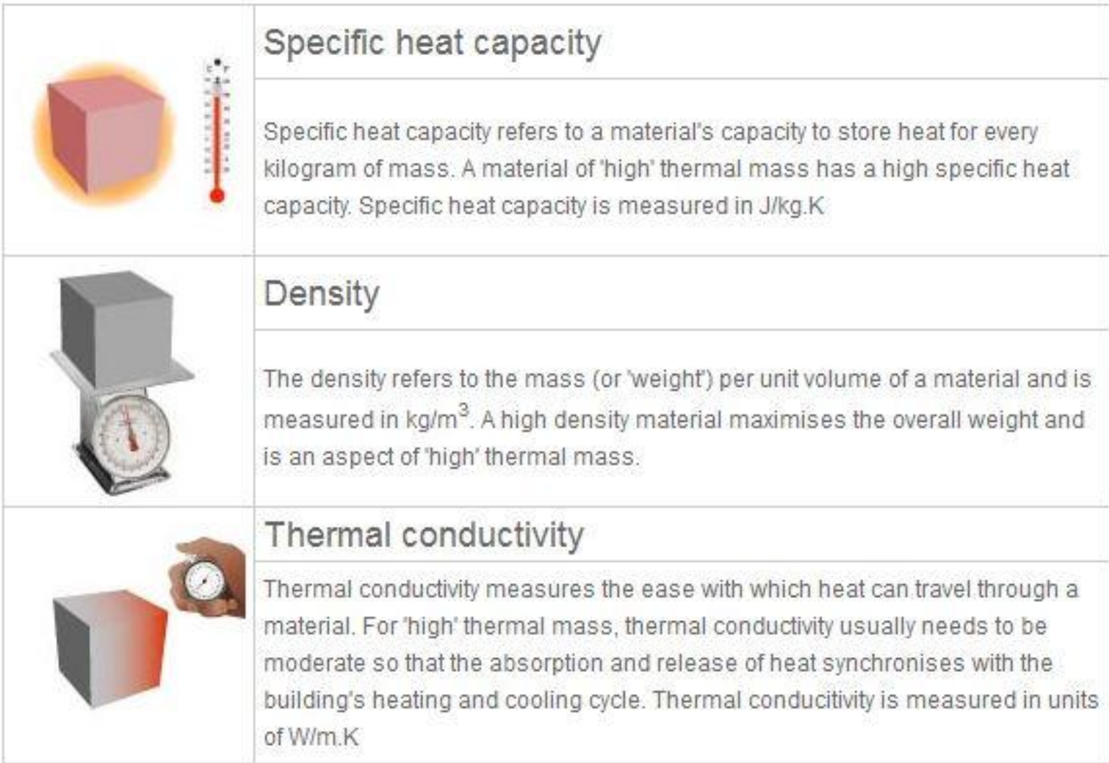

Figure 3.5: Thermal properties of materials suitable for thermal mass utilization [http://www.greenspec.co.uk]

Although the values of density ρ and specific heat capacity C_p, which determine the behavior of these materials, vary with temperature the average prices of these satisfy the relation $\Delta Q = C_p \, \Delta T$ per unit mass. Another key factor that characterizes these materials is the rate at which they can store or emit heat. The density of a material, ρ is the value that indicates how much mass occupies the material per unit volume (kg/m^3). The specific heat capacity , C_p (J / KgK), is the value that shows us how much energy is required to raise the temperature of one kg of material, by one degree Kelvin under steady pressure.

Specific heat under constant volume may be more useful for materials comparison. The value **Cv** or **ρC_p** (J/m^3K) is called storage capacity and indicates how much energy is required to raise the temperature of a cubic meter of a material by one degree Kelvin under constant volume. From the above definitions it appears that the greater the storage capacity of the material, the greater the amount of heating or cooling energy that it can store and also the smallest would be the amount of material needed to store a specific amount of energy. Hence, this is one of the most basic criterions for selecting a material for sensible heat storage, however, as it will be further analysed, in order to select thermal mass materials a number of additional parameters should be checked.

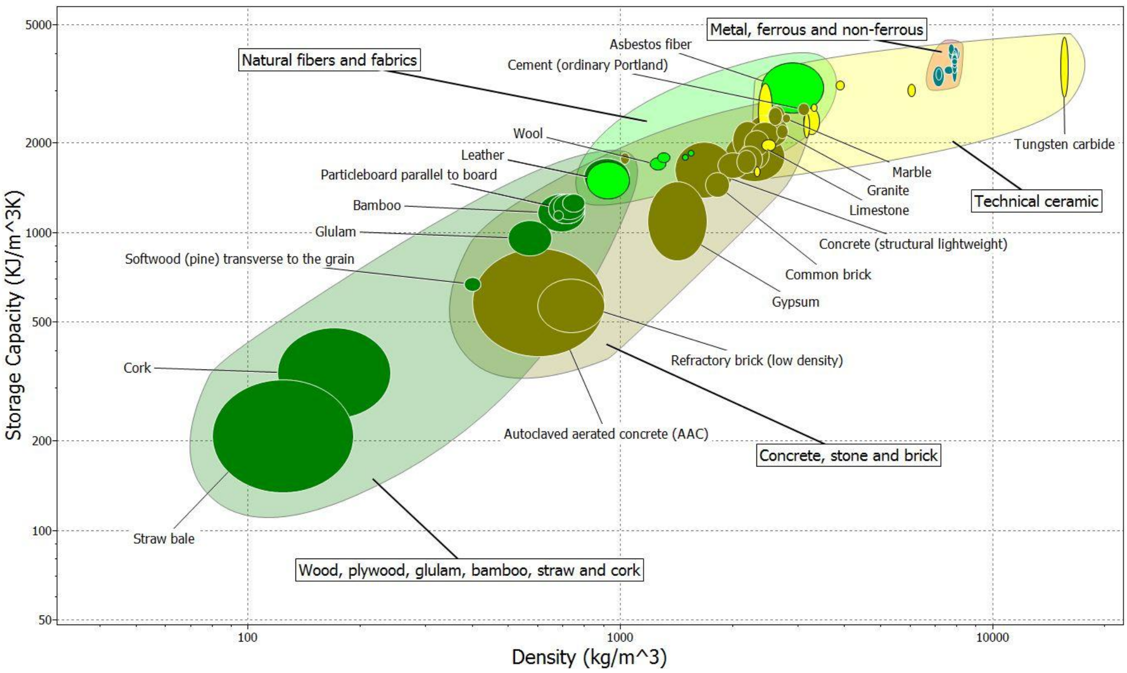

Figure 3.6: Storage capacity vs. density

In Figure 3.6 a bubble chart that shows storage capacity as a function of density has been created using the CES Selector software by Granta [www.grantadesign.com]. There has been a selection of 64 different building materials for comparative analysis, both conventional and unconventional. The materials with high storage capacity are placed in the upper left corner of the diagram. An interesting point that is obvious in figure 3.6 is the allocation of materials over the graph surface. As it is shown in the chart, each category of materials, formulates “families” that are attached to particular areas.

Straw bale and cork are characterized by low density and low storage capacity. That is the reason why, they are usually used as insulation materials. Woods, plywood and the rest of the organic materials appear to have moderate energy capacity similar to gypsum. Cement has the higher storage capacity compared to the other conventional building materials. Concretes perform better than bricks and have similar Cv values with stones. Organic fibers and fabrics perform surprisingly well, particularly asbestos fiber. Undoubtedly, asbestos fiber is a dangerous and cancerous material that has been banned for use in buildings. Nevertheless it has been plotted only for comparative reasons. Technical ceramics and metals appear to have excellent energy capacity, however it is questionable whether they are suitable for thermal mass materials. This is because it is necessary to take into consideration the thermal conductivity of the materials. Consequently, two new values have to be introduced for the effective comparison of thermal mass materials. These values are thermal diffusivity and thermal effusivity**.**

3.3.2 Thermal diffusivity and effusivity

Thermal diffusivity **α** and thermal effusivity **b** are defined in the following equations:

$$\alpha = \frac{\lambda}{\rho * C_p} \quad (\mathrm{m^2/s}) \ (3.1)$$

$$b = \sqrt{\lambda * \rho * C_p} \quad (\mathrm{Ws^{1/2}/m^2K}) \ (3.2)$$

Where:

- λ : material’s thermal conductivity (W/mK)

- C_p : specific heat under steady pressure (J/KgK)
- ρ: material's density (Kg/m^3)

The thermal diffusivity of a material defines how quickly the material responds to temperature variations. A material with high thermal diffusivity will allow a fast heat transfer through it, leading to small heating storage. [Kalogirou et al.2002]. For example a wall that is adjacent to external air should have low values of thermal diffusivity, in order to prevent fast heat exchange with the environment. From equation (1) it results that we can achieve that either by increasing thermal capacity or either by increasing its thermal conductivity.

Thermal effusivity on the other hand, defines the ability of a material to exchange heat with its surroundings and therefore its ability to store heat [Karlsson 2012]. For thermal mass materials, thermal effusivity is the most important factor because, materials with high thermal effusivity would be able to absorb heat fast without extensive temperature variations and release it in later time. The above argument can also be confirmed by checking the following mathematic formula.

Considering the example of the wall that is adjacent to external air, then the amount of thermal energy Q, per unit area, of wall thickness of x, when heated through a temperature interval ΔT gives the following equation:

$$Q = x \, \rho \, C_p \, \Delta T \quad (3.3)$$

This example is a problem of transient heat flow. Thus, the below equation can be expressed as a function of thermal diffusivity, considering that [Fernandez et al. 2010]:

$$x \approx \sqrt{2\alpha t} \qquad (3.4)$$

Rearranging it gives:

$$Q = \sqrt{2t}\, \Delta T \sqrt{\alpha}\, \rho \, C_p$$

Thermal diffusivity is $\alpha = \frac{\lambda}{\rho * C_p}$ thus replacing it gives:

$$Q = \sqrt{2t}\, \Delta T \frac{\lambda}{\sqrt{\alpha}} \quad (3.5)$$

Using equation (x) the result is:

$$Q = b \, \sqrt{2t}\, \Delta T \qquad (3.6)$$

As it is evident from the above equation, thermal effusivity is proportional to stored thermal energy. This explains the fact that thermal effusivity plays such an important role for thermal mass materials. Stahl (2009) reached to similar conclusions. Using the periodic penetration depth simplified model, he calculated that thermal energy storage is proportional to thermal effusivity. In figure 3.7 thermal diffusivity is plotted as function of thermal conductivity. Again technical ceramics and metals seem to perform better as they have the highest values of thermal effusivity. However, considering that suitable materials for heat storage in buildings should have moderate thermal conductivities, materials that are placed in the middle area of the plot such as concretes, stones and bricks plus natural fibers, show the greater performance.

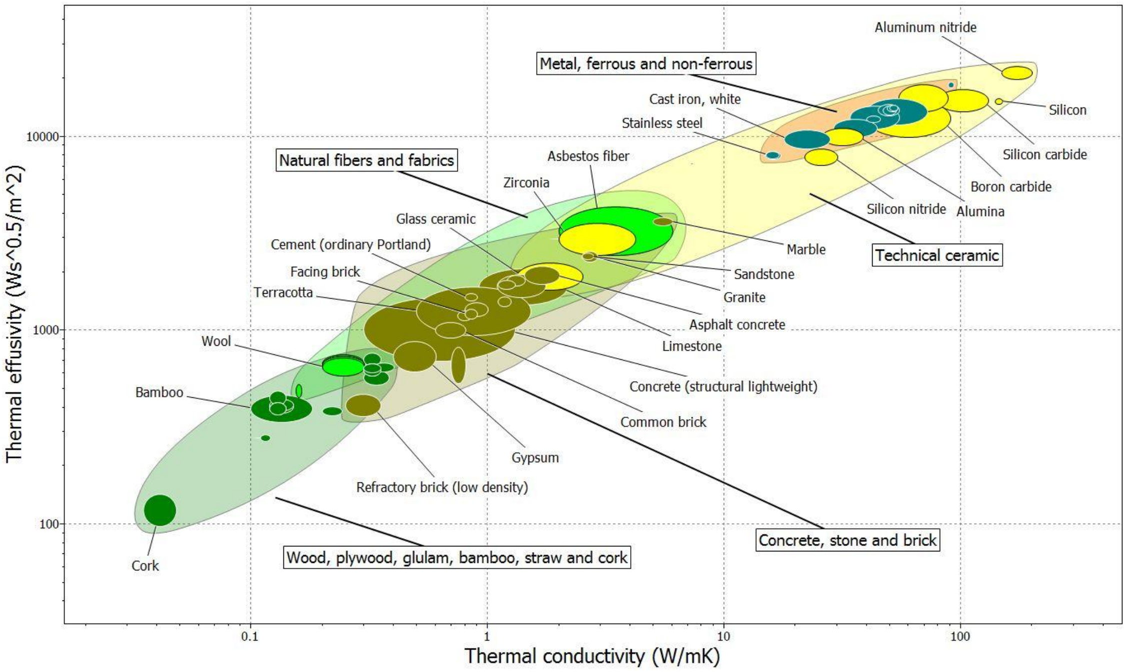

Figure 3.7: Thermal effusivity vs. thermal conductivity

3.3.3 Time lag

The demand for moderate thermal conductivities derives from the need of the synchronization of the charging/discharging process of the material with the building's heating and cooling cycle. An emerging question here is what would be the optimal range of thermal conductivities according to which, materials would have good performance as thermal mass materials. Therefore, it is necessary to introduce the value of time in order to have a clearer view of the materials able to produce the requested time delay.

Considering again the wall example, the *time lag*, measured in hours, is the delay between the outdoor and indoor surface temperature of a wall as a heat wave passes through it [de Saulles 2012]. Time lag is only dependent on wall thickness and diffusivity and not on orientation, temperature variations and other climatic conditions [Thomas et al. 2006]. As it was analyzed in section 1.3 this shift in time is very important for a NZEB in order to overcome the mismatch barrier. For a dwelling, during the day, the energy that is produced on-site from renewables should be stored in the building's envelope in the form of thermal energy and released later when the production stops. Apparently, there is no interest in releasing this thermal energy after 3 or 20h.

For a wall with typical wall thickness of L, the time lag for transient heat and sinusoidal temperature variations is defined as [Thomas et al. 2006]:

$$\varphi = \frac{L}{\sqrt{2\alpha\omega}} \text{ (s)} \quad (3.7)$$

Where:

- L : wall thickness (m)
- α : Thermal diffusivity (m^2/s)
- ω: frequency of the heat wave (Kg/m^3)

For one day cycle the frequency ω is assumed to be constant and is equal to:

$$\omega = \frac{2\pi}{24*3600} \text{ (s)} \quad (3.8)$$

In figure 3.8 the time lag for a wall with typical wall thickness of 25cm (common wall thickness for exterior walls in Greek buildings) is plotted as a function of thermal diffusivity. As it is shown it figure 3.8 technical ceramics and metals have low time lags that range between 0.6h and 3h. According to these results, the above materials seem to be practically unsuitable for thermal energy storage in buildings. Obviously, a theoretical wall made of steel for example, would have smaller thickness than 25cm, because such a thick wall made of steel would be needlessly oversized. However, using these materials in smaller thicknesses would lead to even lower time lags as it results from equation (3.7). On the other hand, wood and the other organic materials including natural fibers have high values of time lags that range between and 10.6h and 21.5h. Combining their high time lags with their low values of thermal diffusivity means that these materials will defuse thermal energy too slowly. Concretes, stones and bricks plus asbestos fiber appear to have the requested time lag for thermal energy storage in buildings that range between 4h for marble and 10.5h for cement. In table 3.1 there is an analytical presentation of materials' time lags for more efficient comparisons.

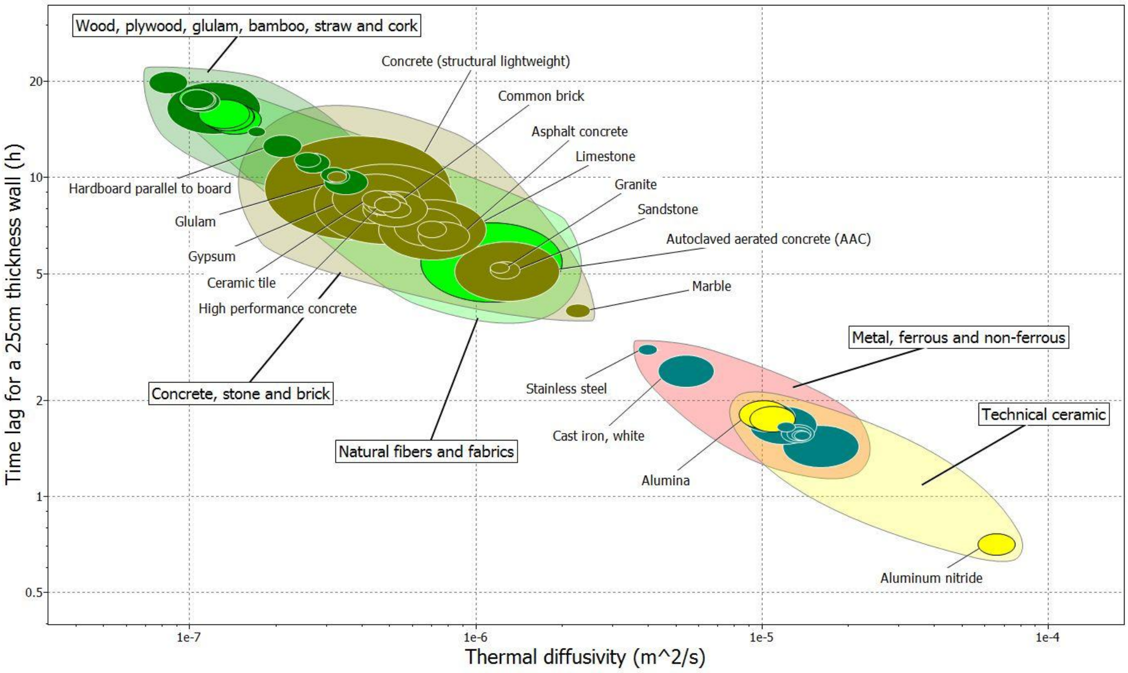

Figure 3.8: Time lag for a 25cm wall vs. thermal diffusivity

3.3.4 Optimal thickness

The optimal thickness of thermal mass materials for periodic thermal energy storage has been studied recently by Stahl (2009) and Ma and Wang (2011). Both studies showed that there is an optimal thickness for each material above which there is no considerable thermal energy storage. Stahl found that for sinusoidal temperature variations, this thickness is close to periodic penetration depth. Periodic penetration depth depends on the material's thermal diffusivity as it shown on equation (3.9):

$$d_p = \sqrt{\frac{2\alpha}{\omega}} \text{ (m)} \quad (3.9)$$

Where:

- α : Thermal diffusivity (m^2/s)
- ω: frequency of the heat wave (Kg/m^3)

For one day cycle the frequency ω is assumed to be constant and is equal to:

$$\omega = \frac{2\pi}{24*3600} \text{ (s)} \quad (3.10)$$

In figure 3.9 periodic penetration depth is plotted as a function of thermal diffusivity. The similarity of this figure with figure 3.9 is quite remarkable but not unexpected. This is because both values of time lag and penetration depth depend on thermal diffusivity. It is clear that a material with low thermal diffusivity will allow heat to penetrate it in greater thicknesses and thus it will need more time to release that heat back. In table 3.1 there is a presentation of periodic penetration depths for building materials.

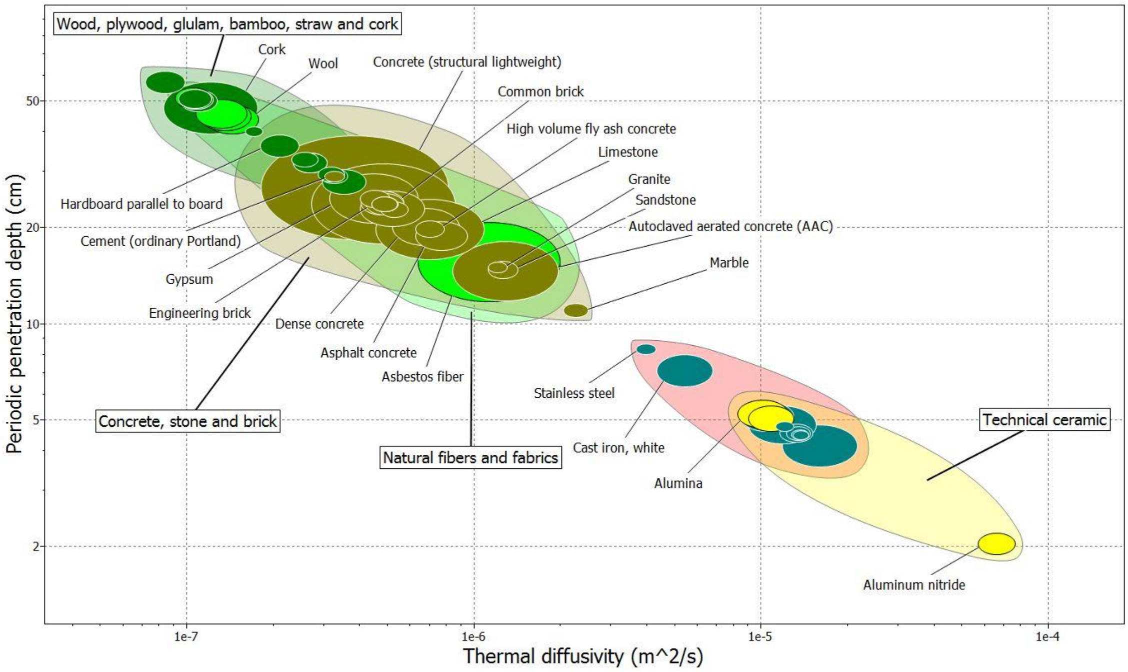

Figure 3.9: Periodic penetration depth vs. thermal diffusivity

Table 3.1 : Average values of time lag for a 25cm thickness wall and penetration depth for building materials

Material	Time lag (h)	Penetration depth (cm)
High carbon steel	1.08	4.53
Coated steel, steel, galvanized	1.56	4.48
Low carbon steel	1.57	4.50
Medium carbon steel	1.59	4.57
Wrought iron	1.66	4.78
Low alloy steel	1.69	4.87

Silicon nitride	1.76	5.07
Alumina	1.82	5.24
Cast iron, white	2.50	7.18
Coated steel, stainless steel, terne coated	2.88	8.29
Stainless steel	2.90	8.34
Titanium alloys	3.40	9.78
Marble	3.84	11.05
Sandstone	5.14	14.80
Autoclaved aerated concrete (AAC)	5.20	15.00
Granite	5.24	15.05
Asbestos fiber	5.65	16.25
Asphalt concrete	6.60	19.00
High volume fly ash concrete	6.90	19.85
Limestone	7.03	20.20
Dense concrete	7.07	20.35
Reactive powder concrete	7.94	22.85
Refractory brick (low density)	8.06	23.15
Facing brick	8.25	23.70
Engineering brick	8.26	23.80
High performance concrete	8.26	23.80
Common brick	8.36	24.10
Ceramic tile	8.60	24.75
Terracotta	8.62	24.90
Gypsum	8.77	25.20
Glulam	9.76	28.10
Concrete (structural lightweight)	9.96	28.65
Softwood (pine) parallel to the grain	10.10	29.10
Cement (ordinary Portland)	10.11	29.05
Hardwood (oak) parallel to the grain	10.26	29.50
Medium density fiberboard parallel to board	11.15	32.05
Particleboard parallel to board	11.15	32.05
Plywood parallel to board	11.40	32.75
Straw bale	11.67	33.65
Hardboard parallel to board	12.60	36.30
Softwood (pine) transverse to the grain	13.95	40.15
Wool	15.30	44.05
Silk	15.70	45.10
Flax	15.70	45.15
Hemp	15.70	45.15
Cotton	16.00	45.95
Cork	16.90	48.55
Bamboo	17.20	49.55

3.3.5 Emissivity and thermal expansion coefficient

Apart from conduction and convention, radiation is another way of heat transfer. Thermal radiation is the form of energy emitted by bodies because of their temperature. Thermal radiation is a completely natural phenomenon and should not be confused with other forms of electromagnetic radiation such as X-rays, the gamma-rays, microwaves etc, which are not related to temperature. All the bodies at a temperature above absolute zero emit thermal radiation.

Material's emissivity ε is the parameter that defines the ability of a material to transfer heat by radiation. Emissivity has values in the range of $0 \leq \varepsilon \leq 1$ and it shows how closely a surface of a material approximates an ideal "black body" which is the perfect heat emitter and for which $\varepsilon = 1$ [Karlsson 2012]. According to Stefan-Boltzmann law the amount of energy escaping from a surface as radiation is given by the following equation (3.11):

$$Q_{emit} = \sigma \varepsilon A T^4 \quad (3.11)$$

Where:

- σ : the "Stefan-Boltzmann" constant, which is equal to $5.67 * 10^{-8}$ W/m^2K^4
- ε: emissivity of the surface, with values in the range of $0 \leq \varepsilon \leq 1$
- A : Area of the surface (m^2)
- T: Temperature on the surface of the material (K)

Thermal mass materials should have high values of emissivity. This is because low emissivity of a material indicates that the greater proportion of thermal radiation incident on the material's surface will be reflected than absorbed and stored. Materials with low emissivity surfaces should be preferred for external building elements with the intention of protection against solar radiation. The opposite sense should prevail regarding internal surfaces. Generally, materials with high emissivity should be preferred for indoor spaces in order to be able to absorb internal gains and heat surpluses.

Thermal radiation plays an important role for thermal mass materials especially in cases of active use of thermal mass such as hydronic systems like under-floor heating but also in cases of passive systems like Trombe walls. Concerning particularly the applications of active thermal mass, which are subject to significant temperature changes, another parameter is also important. It is the thermal expansion coefficient. Thermal expansion and contraction of the materials could cause serious material failures, like cracks, especially if materials with different thermal expansion coefficient are associated together.

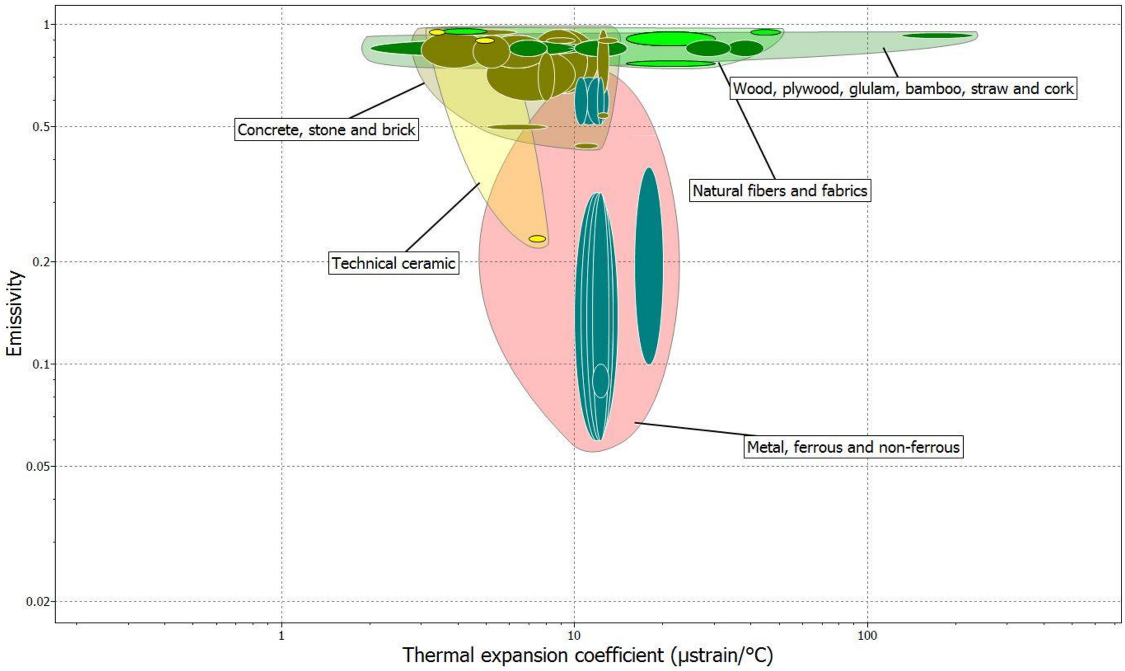

Figure 3.10a: Emissivity vs. thermal expansion coefficient

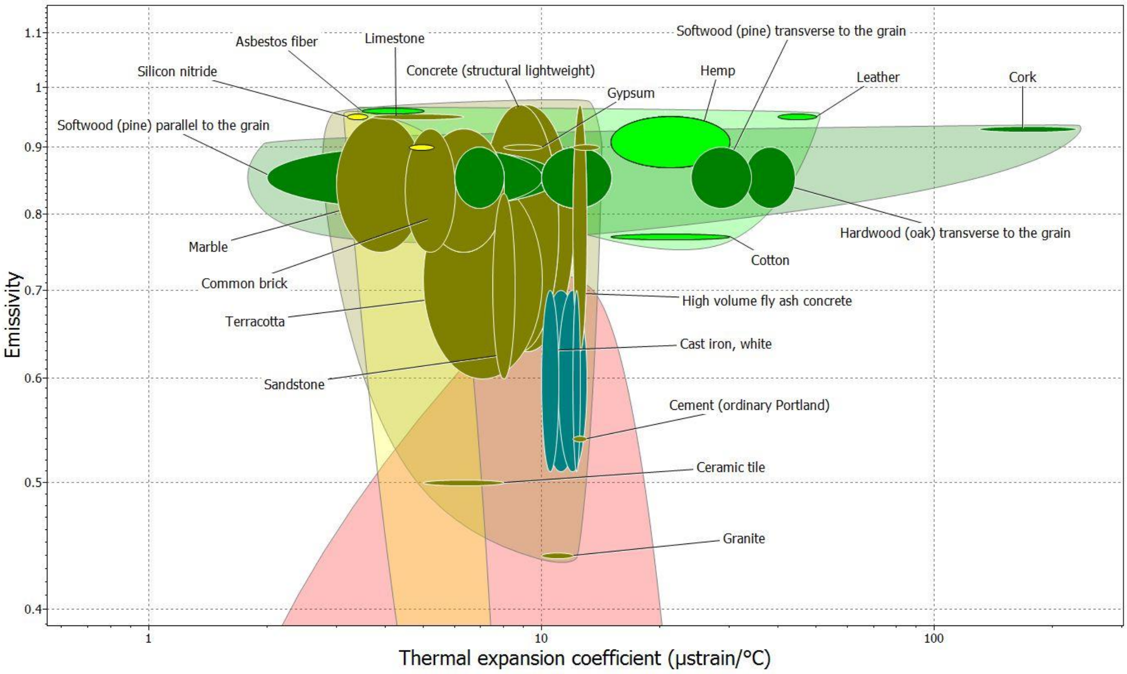

Figure 3.10b: Emissivity vs. thermal expansion coefficient

In figure 3.10a emissivity is plotted as a function of thermal expansion coefficient, practically two independent parameters in terms of physical attributes. Nevertheless their combination in a common graph could lead to useful conclusions and further investigation. As it is demonstrated in figure 3.10b asbestos fiber and limestone have excellent performance. Likewise, most of the concretes stones and bricks appear to have high values of emissivity and simultaneously a satisfactory response to thermal contractions-expansions. However, granite, ceramic tiles and cement lagging behind when compared to the other materials of the same group due to their low values of emissivity. Woods and natural fibers exhibit high values of emissivity but their thermal expansion coefficient values vary significantly. Most of technical ceramics perform well, while metals fail to impress except for cast irons. In this point it must be highlighted that whatever the value of emissivity of a material is, its radioactive properties could be enhanced by the use of surface coatings, since thermal radiation is considered as a surface phenomenon.

3.3.6 Mechanical behaviour

Although the main purpose of this thesis is to analyze the properties of materials in terms of heat storage, should not be neglected the fact that, this work refers to building materials, which their main and obvious characteristic is their structural behaviour. The bearing structure of the buildings such as columns, beams and slabs or masonry walls, as well as the non-bearing elements such as internal walls, consist mainly of thermal mass materials. Therefore, it is important to have an outlook of the thermal mass materials' structural safety and durability. In other words thermal mass materials should serve structural purposes in buildings' construction. Moreover, in countries like Greece where buildings are subject to seismic loads, there are additional requirements for the strength of building materials. Building materials should have a satisfactory elasticity in order to avoid permanent deformations.

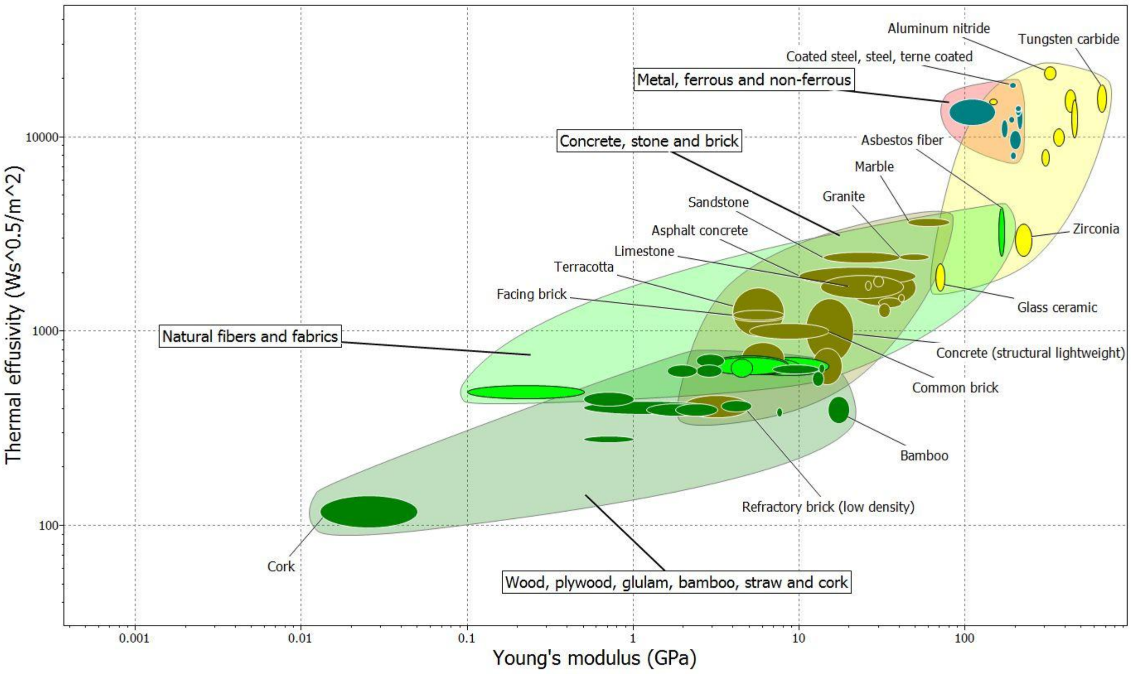

Figure 3.11a: Thermal effusivity vs. Young modulus

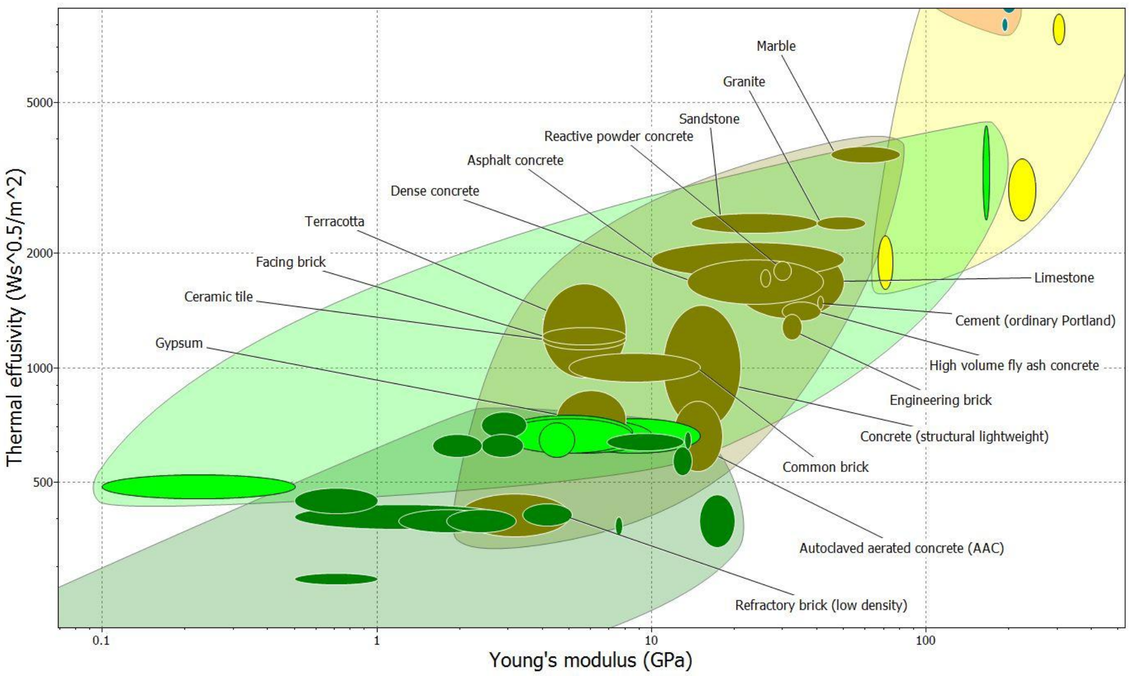

Figure 3.11b: Thermal effusivity vs. Young modulus for conventional materials

In figure 3.11a thermal effusivity is plotted as a function of Young's modulus, which is the ratio of stress to strain when the deformation is totally elastic. Once more two independent parameters are plotted together and it is quite interesting to have a view of the material's performance combining these two parameters. As it is evident in figure 3.11a technical ceramics and metals combine both high effusivity and high elasticity. Asbestos fiber performs well for one more time, but as it was mentioned before it has been plotted only for comparative reasons, while the other natural fiber materials fail to impress. The same stands for wood and the rest organic materials. In figure 3.11b the performance of conventional building materials is shown.

3.3.7 Embodied energy and CO_2 footprint

Embodied energy is the total energy required for the extraction, processing, manufacture and transportation of building materials to the construction site. Energy consumption produces CO_2 emissions, which contribute to the greenhouse effect. Consequently it is considered very important when it comes to calculating the environmental impact of building materials and systems. However, it should not be confused with the Life Cycle Assessment (LCA), as it does not consider the impacts of materials over their life. The processes of operation and disposal are not considered.

For many years the construction industry ignored the embodied energy of the building, because it is relatively insignificant compared to the operating energy of the building over its lifetime. Traditionally, the construction industry focused on finding solutions on reducing the operational energy of a building through its lifetime and improving its energy efficiency, than to deal with its embodied energy. However, researches has shown that as the operational energy declines steadily, the percentage of embodied energy (including energy required for maintenance) becomes more important through the successful reduction of the operational energy [Tucker et al. 1993].

Embodied energy is measured as the quantity of non-renewable energy per unit of building material. It is expressed in megajoules (MJ) or gigajoules (GJ) per unit weight (kg or tones) or area (m^2). However, the process of calculating embodied energy is complex and involves numerous sources of data. In CES selector software, embodied energy is the energy required to make 1 kg of the material from its ores or feedstocks. Data are approximate, but still useful in ranking materials. According to the same approach the CO_2 footprint of the materials is the mass of carbon dioxide (CO_2), in kg, produced and released into the atmosphere, as a result of the production of one kg of the material.

In figure 3.12 thermal effusivity is plotted as a function of embodied energy of primary production, in an effort to search for the materials with increased ability to store heat and simultaneously to present low impact to the environment. As it is shown on the graph each category of materials are attached to certain different areas as they almost don't share common domains.

Metals, technical ceramics and natural fibers present high values of embodied energy and clearly they cannot be characterized as ecological materials. On the other hand, woods and the rest of organic materials have slightly lower embodied energy but too low values of thermal effusivity.

Evidently, concretes, stones and bricks, are the category of materials with the lowest values of embodied energy and particularly stones, except for granite, seem to have the greatest performance. This is because stones, except for granite which requires further processing, require energy only for their extraction, which makes them environmentally friendly materials.

Limestone stands out as it combines the lowest embodied energy values and good enough thermal effusivity values. Sandstone present also low values of embodied energy and slightly higher values of thermal effusivity than limestone, while marble is the material with the highest thermal effusivity values of the family.

Concretes also show excellent performance with low embodied energy values and values of thermal effusivity that vary according to the kind of concrete.

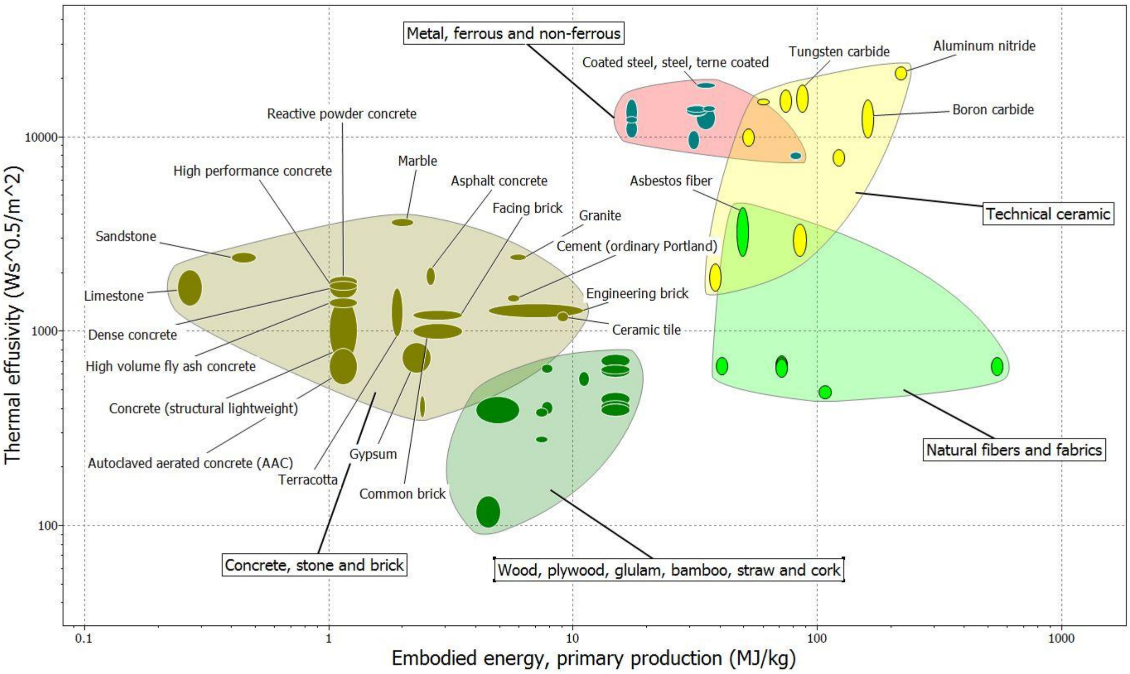

Figure 3.12: Thermal effusivity vs. embodied energy

Terracotta, gypsum, bricks and cement show higher values of embodied energy due to the fact that they require additional processing that generates CO_2 emissions. This is also depicted in figure 3.13. In figure 3.13 thermal effusivity is plotted as a function of CO_2 footprint of primary production. The results in this chart are similar to the previous one. However, this chart highlights with the most emphatic way that materials which require more machining and processing produce more CO_2 emissions and thus they are considered more energy intensive.

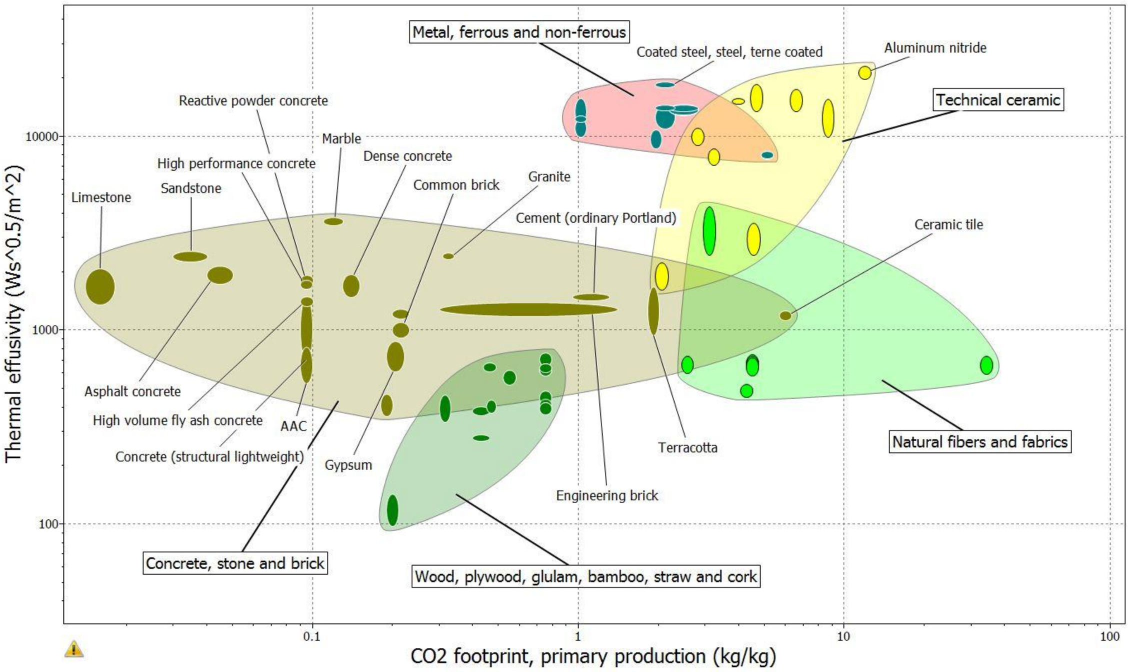

Figure 3.13: Thermal effusivity vs CO_2 footprint

4 Selection of thermal mass materials

4.1 Selection strategy

In the previous section the properties of thermal mass materials for periodic thermal energy storage were presented. Thermophysical and other properties were combined and plotted together in order to facilitate their classification and comparison. In this section a selection of materials will be made by inserting various constraints. An exhaustive selection strategy, which includes an elimination process, will lead to the materials that satisfy all the constraints that were initially posed.

According to the selection strategy introduced by Ashby (2005) the performance of a material is based on three guidelines:

- The functional requirements (the need to store heat, to carry loads etc.)
- The geometry
- The properties of the materials (including cost, embodied energy etc.)

The material's performance *P* can be written as an equation with the following form:

P = f [(functional requirements), (geometry), (properties)] (4.1)

Then, the procedure consists of four basic steps:

1. Definition of functional requirements
2. List of constraints
3. List of objectives (e.q cost minimization, CO_2 footprint minimization)
4. List of free variables (usually dimensions, shape and obviously the choice of material)

Based on this approach Fernandez et al. (2010), developed a selection strategy called material index. Under this strategy he managed to perform safe material selection combining two or more complex parameters. For example, if the main object is to minimize the cost of the material, the cheapest material that simultaneously satisfies all the constraints, is the best choice. Moreover, he highlighted that when there are two or more objectives that have to be fulfilled and there is an emerging conflict between them, a multi-objective optimization should be used for reaching a compromise between conflicting objectives.

In the present work a selection of materials based on the above strategies will be implemented. Following the first step the functional requirement is easily identified. This is the selection of the best thermal mass materials for periodic thermal energy storage in net zero energy buildings. Therefore, the materials in order to be able to perform the above role, should meet the constraints that are summarized in table 4.1.

During the selection process 127 different materials both conventional and unconventional will be checked. An attempt to discover new alternative materials that meet the constraints will be made. New families of materials will be introduced for selection such as glasses, polymers, elastomers and synthetic fibers.

Table 4.1 : Range of materials properties for periodic thermal energy storage

Thermal Delay (h)	Emissivity	Young's modulus (GPa)	Thermal expansion coeff. (μstrain/^{o}C)
$6 \leq \phi \leq 8$	$\varepsilon \geq 0.7$	$E \geq 5$	$a \leq 100$

The next step involves the setting of objectives. Three different objectives will be set. First, is to find out the best materials for maximum periodic energy storage without any other restrictions. Second, is to find out the best materials for energy storage but at the same time with the lowest embodied energy. Third is to find out the best materials for energy storage and simultaneously with the lowest cost. According to selection strategy all objectives have to be translated into performance equations. The following list shows the objectives:

1. Maximization of thermal energy storage
2. Minimization of embodied energy
3. Minimization of cost

According to the fourth step the free variables will be the materials choice and dimensions.

4.2 Maximum thermal energy storage

The main concern of this work is the first objective which is to find thermal mass materials with the highest ability to store thermal energy. At first glance, one might argue that in order to achieve that it suffices to maximize the material's storage capacity ($\rho\ C_p$). However, this is misleading because, as it was analyzed in the previous section, by this way the time value, which is essential for periodic thermal energy storage, would be ignored. This approach would make sense if the objective was simply to select materials for sensible energy storage. Thus, as the main object is to find thermal mass materials which have to diffuse internally heat or coldness by conduction during the day, the values of effusivity or diffusivity should be introduced to the function of thermal energy storage. Hence, the first objective can be translated into performance equations, using the equations (4.2) and (4.3):

$$Q = b\ \sqrt{2t}\ \Delta T \quad (4.2)$$

$$Q = \sqrt{2t}\ \Delta T \frac{\lambda}{\sqrt{\alpha}} \quad (4.3)$$

In order to reach the objective of maximizing storage ability, materials with the highest thermal effusivity should be selected. This is achieved by choosing materials with a high value of:

$$P_1 = \frac{\lambda}{\sqrt{\alpha}} \quad (4.4)$$

Thus, the first performance index has been created. Applying logarithms in the above equation and rearranging the result is:

$$\log\alpha = 2\log\lambda - 2\log P_1 \quad (4.5)$$

According to the above equation, in figures 4.1a and 4.1b thermal diffusivity is plotted as function of thermal conductivity, in a logarithmic scale. Materials in this plot where filtered using the constraints of table 4.1. The failed materials are marked with gray colour. The materials with the highest performance index are those in the bottom right of the chart. For a given guideline with a slope of (2) the materials below this line perform better than those located over the line. Moving the guideline parallel, the designer can easily identify which materials have the greatest performance. This is shown in figure 4.1a as the guideline is moving parallel from right to the left the best materials are revealed one-by-one. This enables the designer to proceed to safe selections and to perform material ranking.

As it occurs from the current strategy, limestone is the best material that has the maximum effusivity and simultaneously manages to meet all the initial constraints. Although asbestos fiber had the greatest performance, it is excluded from the selection because it is a dangerous and cancerous material that has been banned from use in buildings. In the second place asphalt concrete is found. However, asphalt concrete is not recommended for use in building's indoor spaces because when it is heated it may emit toxic fumes. Very close to asphalt concrete in third and fourth place respectively, terracotta and lightweight concrete are found. Consequently, limestone following by terracotta and concrete are the best thermal mass materials for maximum periodic thermal energy storage in buildings.

In figure 4.1b all the materials that meet all the initial constraints are shown. From the 127 materials that entered the selection process only 19 managed to pass through the filtering. The attempt to find out new unconventional materials suitable for periodic thermal energy storage did not lead to impressive findings. From the additional materials Vycor and Pyrex from the glass family and glass fiber from synthetic fibers family show some potential.

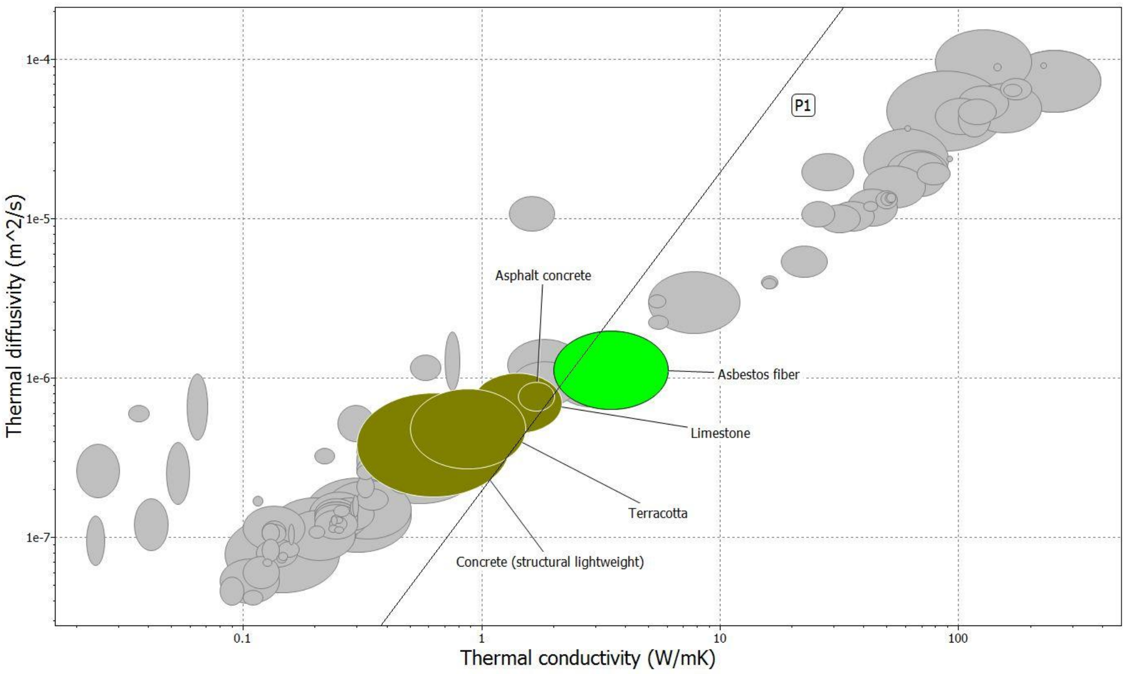

Figure 4.1a: Performance index P_1 (best materials)

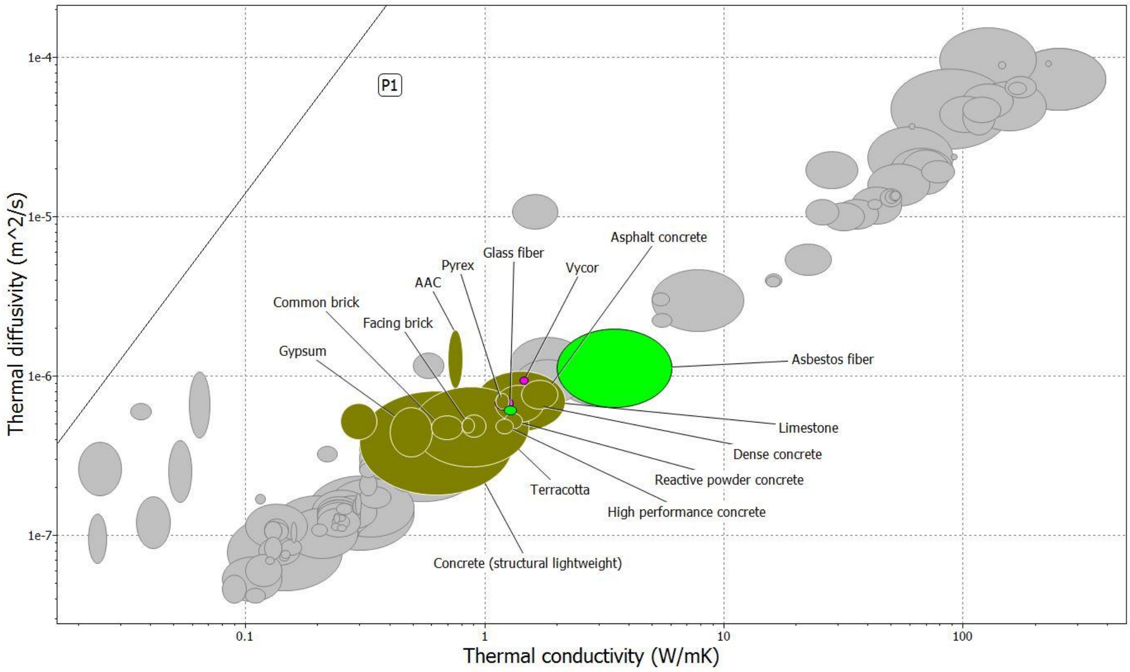

Figure 4.1b: Performance index P_1 (all qualified materials)

Another interesting point shown in figure 4.1b is the performance of the bricks. As it is obvious they lagged behind compared to the concretes. Nevertheless in Greece the use of bricks remains the most popular way for walls construction in new or refurbished buildings. The fact that bricks are not so efficient materials in terms of thermal energy storage has to be taken into account from the building designers.

4.3 Minimization of embodied energy

The next objective is to find the materials with the minimum embodied energy but still suitable enough for periodic thermal energy storage. In order to do that, according to the selection strategy, the corresponding performance index has to be created. Following the methodology proposed by Jeanjean et al. 2013, the embodied energy (E_e) per unit of mass (4.6) can be written as:

$$E_e = mE_{em} \quad (4.6)$$

Where:

- E_e: embodied energy for the primary production of materials (MJ)
- m: mass of the materials
- E_{em}: embodied energy per kg (MJ/kg)

Assuming that material thickness is x (m), material area is A (m^2) and using the equation (4.7), the above equation can be written as:

$$E_e = mE_{em} = \rho VE_{em} = \rho\,(xA)\,E_{em} = A\sqrt{2\alpha t}\,\rho E_{em} \qquad (4.7)$$

Observing the above equation it can be easily concluded that the objective to minimize embodied energy depends on different variables. Except for the variables that are geometrical (area) or functional (time), the rest of them depend on materials properties. So in order to reach the objective of embodied energy minimization, materials with high values of P_2 should be selected.

$$P_2 = \frac{1}{(\alpha)^{1/2}\rho E_{em}} \qquad (4.8)$$

Thus, the second performance index has been created. Continuing with the same methodology applying logarithms in the above equation and rearranging the result is:

$$\log\alpha = -\,2\log P_2 - 2\log(\rho E_{em}) \qquad (4.9)$$

According to the above equation, figures 4.2a and 4.2b have been created showing the plots of α vs. ρE_{em}, in a logarithmic scale. In this case the materials with the highest performance index will be those in the bottom left of the chart because of the negative slope (-2) and negative y intercept. For a given guideline with a slope of (-2) the materials below this line perform better than those located over the line. Moving the guideline parallel from left to right the best materials are revealed one-by-one.

As it is evident from the figure 4.2a limestone proves that it is an excellent material as it in the first place once more. However, this result was not unexpected because limestone requires energy only for its extraction. In the second place autoclaved aerated concrete (AAC) is found. AAC is a low density lightweight concrete which is a result of many small air bubbles in its composition. Concrete is found in the third place showing again admirable performance proving that it is also an eco-friendly material. Figure 4.2b shows the performance of the rest materials. It can be seen that all the rest concretes are following, while terracotta, bricks and asphalt concrete fell behind due to their high processing of manufacture.

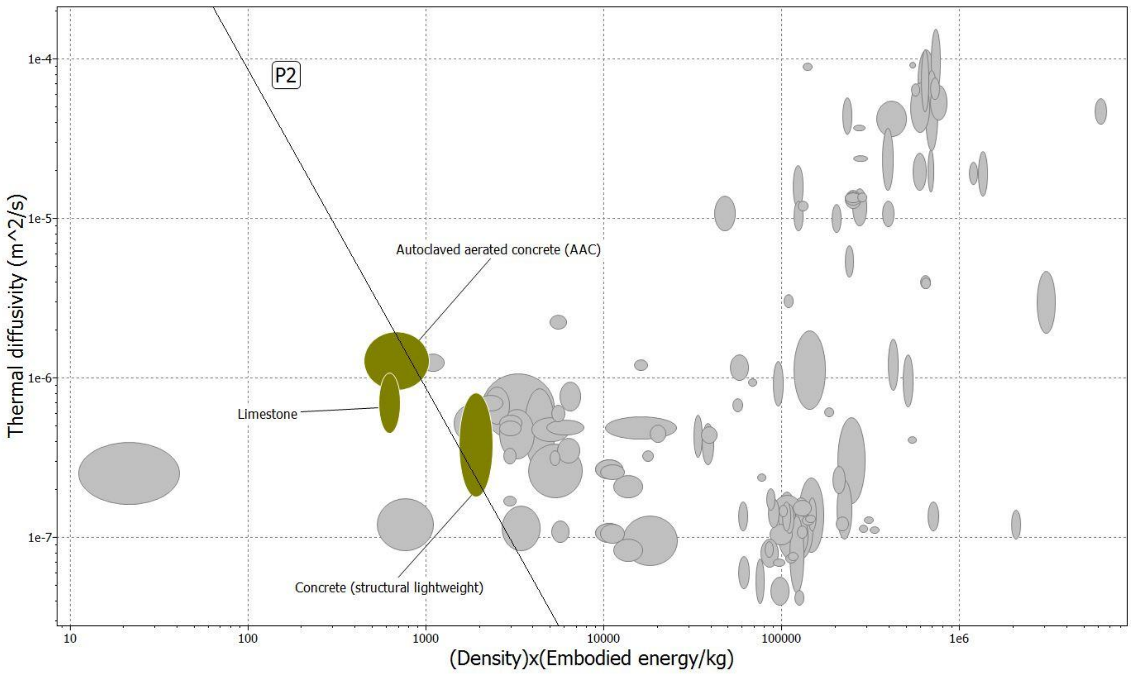

Figure 4.2a: Performance index P_2 (best materials)

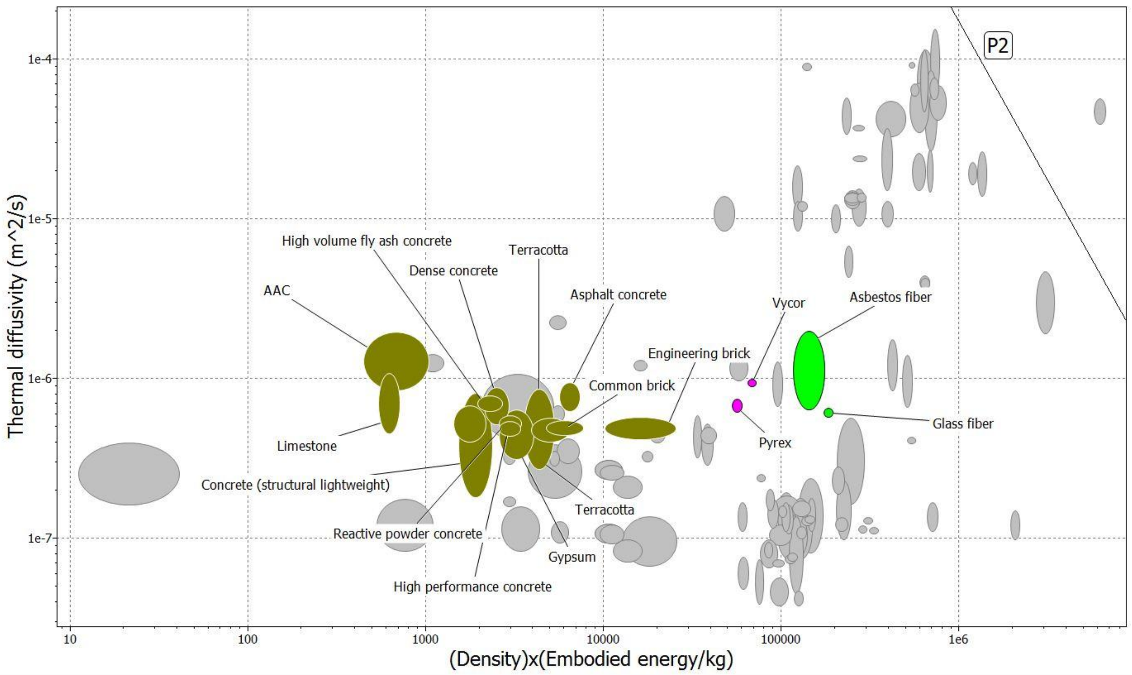

Figure 4.2b: Performance index P_2 (all qualified materials)

4.4 Minimization of cost

The cost of materials is a factor that cannot be ignored when selecting thermal mass materials for periodic energy storage. Besides, one of the final purposes of using thermal mass materials in buildings is energy savings and hence cost savings. However, the most cost effective solution may not always be the one with the initial lower cost. Materials that combine both high thermal energy storage and low cost may be preferable than the cheapest materials. Even so, the final selection of the material depends on the designer's pursuits.

The objective to find the cheapest materials for periodic thermal energy storage can be reached by implementing the same procedure. In this case the cost per unit of mass (C) can be expressed using the following equation:

$$C = mC_m \quad (4.9)$$

Where:

- C: Cost of the materials (€)
- m: mass of the materials
- C_m: cost per kg (€/kg)

Similarly to the previous objective, assuming that material thickness is x (m), material area is A (m^2) the above equation can be written as:

$$C = A\sqrt{2\alpha t}\,\rho C_m \qquad (4.10)$$

Thus, in order to reach the objective of cost minimization, materials with high values of performance index P_3 should be selected.

$$P_3 = \frac{1}{(\alpha)^{1/2}\rho C_m} \qquad (4.11)$$

Applying logarithms in the above equation and rearranging the solution is:

$$\log\alpha = -2\log P_3 - 2\log(\rho C_m) \qquad (4.12)$$

According to the above equation, figures 4.3a and 4.3b have been created showing the plots of α vs. ρC_m, in a logarithmic scale. The materials with the highest performance index will be those in the bottom left of the chart because of the negative slope (-2) and negative y intercept. For a given guideline with a slope of (-2) the materials below this line perform better than those located over the line. The method for the selection and ranking of materials is again the same. By moving the guideline parallel from left to right, the best materials are revealed one-by-one.

In figure 4.3a it can be seen that AAC and concrete are sharing the top. AAC is the cheapest material for periodic thermal energy storage as it meets the initial constraints. Very close to the first rank is lightweight concrete. It should be noted that concrete is found on the top positions in every objective that was set. In figure 4.3b is shown that asphalt concrete and the rest concretes are following. Terracotta, common bricks and limestone are more expensive materials than concretes. Although limestone had a brilliant performance in the previous sections, this time, its high labour cost for carving and building moves it away from the top.

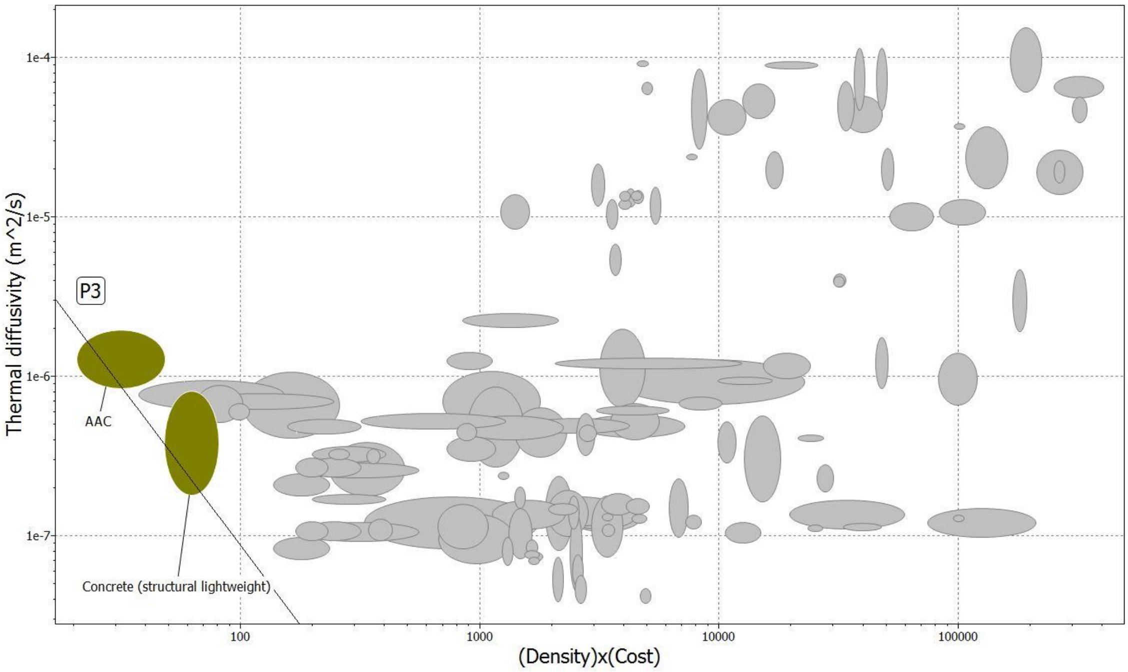

Figure 4.3a: Performance index P_3 (best materials)

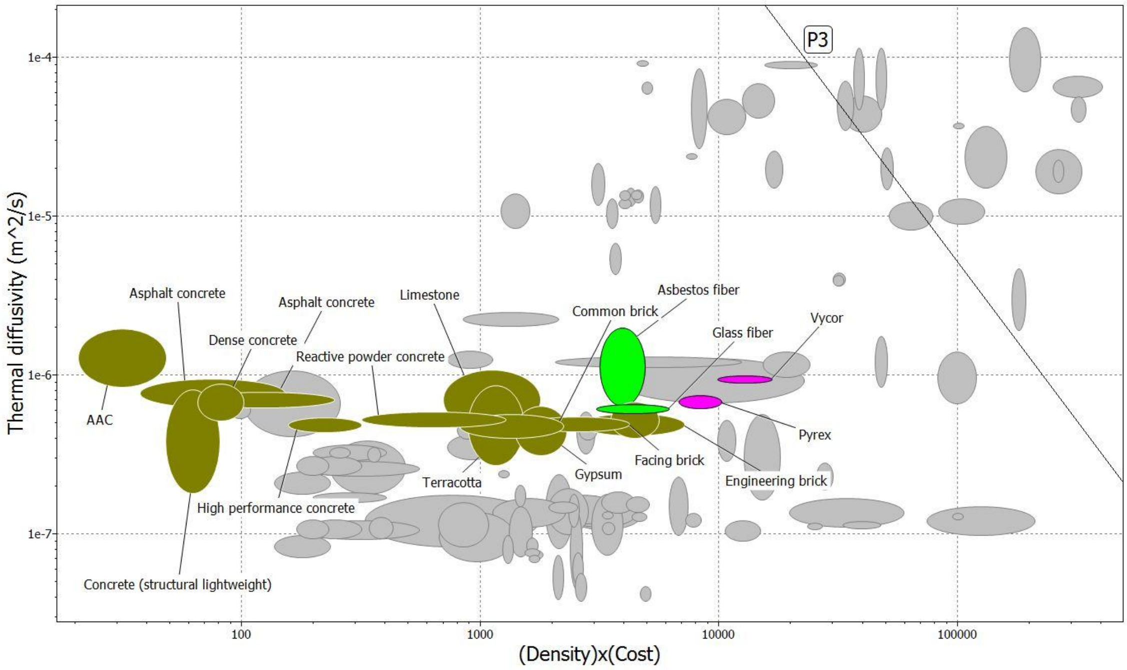

Figure 4.3b: Performance index P_3 (all qualified materials)

4.5 Final selection

Summarizing the above findings, limestone, lightweight concrete and autoclaved aerated concrete (AAC) stood out.

Limestone is the best material for periodic thermal energy storage in buildings as it combines excellent storage ability (max effusivity) and simultaneously the lowest embodied energy. Limestone is a sedimentary rock composed primarily of calcium carbonate. The commercial term “limestone” is often used to describe dolomite, dolomitic limestone, oolitic limestone, and travertine [Dolley 2007]. Limestone is the most common stone in Greece and is used for the construction of buildings from the ancient years until the mid-twentieth century when it was replaced by materials such as brick and concrete (figure 4.4). The high labor cost for the carving and building of limestone in combination with its low speed of construction, flexibility and workability, often discourages designers from its use. However, the use of limestone in building construction can be increased, especially if it is proved that it contributes significantly to the energy savings of a building.

Figure 4.4: Valtadorion High School in Kozani, Greece was built in 1899 and is made of limestone blocks with 60cm thickness

AAC on the other hand, is the cheapest material that can be used for periodic thermal energy storage. AAC which is usually found in the form of blocks is a foamed or cellular concrete that is produced by adding a foaming agent to the concrete mix in order to entrap air bubbles during the curing process, which involves steam heating ("autoclaving") [Bave et al. 1978] (Figure 4.5). The main advantages of AAC compared to limestone or common bricks, are its low thermal conductivity values which could lead to reduced insulation requirements, its light weight, its speed of construction and its fine workability that allows accurate cutting with reduced solid wastes. All the above properties of AAC contribute to its low cost. However its low thermal effusivity makes it less effective material for heat storage when it is compared with other materials.

Figure 4.5: AAC block close up [www.e-crete.com]

As it is obvious, the selection process often leads to conflicts amongst the initial objectives. In this case a multi-objective optimization should be used for reaching a compromise between conflicting objectives. According to this approach, the selection of lightweight concrete seems to be ideal. Besides, concrete recorded an excellent performance in all three objectives that were set, proving that it is the material which combines high storage ability, low embodied energy and low cost.

Lightweight concrete consists of lightweight aggregates and it can be found in the form of pre-cast, in-situ or blocks. Pre-cast means that the concrete is cast to readymade building elements like walls before its transportation to the site. In-situ means that building elements are constructed in the site. Because of its high drying shrinkage and its tendency to show microcracks, it is often reinforced. However, concrete blocks are usually used without reinforcement. In Greece, concrete blocks had been used extensively in buildings especially during sixties and seventies. However, their low values of thermal conductivity, their high weight and low sound insulation made them less attractive when they compared with bricks so their use was limited.

Although, concrete seems as the most convenient solution, the final selection of the thermal mass materials depends on various parameters which have to do mainly with the integration and performance of the materials in a NZEB. For this reason the selection would be safer if a simulation of the materials under conditions similar to those existing in a NZEB, would take place. In the following chapter a simulation process will be implemented. The materials that will be used will be the above three materials that resulted through the filtering process. The conventional way of constructing buildings in Greece consists primarily of buildings with reinforced concrete frame and brick walls. Through the simulation process it will be examined if the use of limestone, concrete or AAC walls, outperforms in comparison with the conventional construction method of brick walls.

5 Simulated dynamic thermal behaviour of a test cell model

5.1 Simulation methodology

In the previous section the best materials for energy storage in buildings were selected. These materials are limestone, AAC and concrete. In this section the energy performance of walls constructed by the selected materials will be compared with the performance of common brick walls. The purpose of this comparative analysis is to investigate if there is an advantage of the use of these materials in terms of energy savings. Furthermore, the potential of using these materials in order to overcome the mismatch barrier between energy production and demand in a NZEB will be also investigated.

In order to perform an effective comparative evaluation of the selected thermal mass materials, simulation tests under the climatic conditions of the four climatic zones of Greece, will be implemented. Climatic data for four Greek cities (Heraklion, Athens, Thessaloniki, Kastoria) that correspond to each zone will be used (Figure 5.1). The four climatic zones have been defined by the Greek Regulation of the Energy Performance of Buildings (KENAK) [Official Gazette of the Hellenic Republic, Regulation of Energy Performance of Buildings].

KENAK is the only existing legal framework in Greece, that addresses the buildings' energy performance and it is based on Directive 2010/31/EC. Since there is no other available legislation or directive that determines the specifications of a NZEB, all the necessary data (U-values, internal gains, infiltration etc) that are used for the simulation are in accordance with KENAK.

Below a brief description of the simulation steps and the different cases that will be examined is demonstrated.

- Case 1: Development of the reference model with exterior walls made of brick. Constant thermostat set point between 20 ^{o}C and 26 ^{o}C.

Simulation runs for each material of annual heating and cooling energy loads under the four climatic zones weather data.

- Case 2: Copy the model from case 1. Addition of internal thermal mass in the form of interior walls from the same materials as the external walls. Simulation runs for each material.
- Case 3: Copy the model from case 2. Simple pre-cooling at 23 ^{o}C between 9am and 15pm. Simulation runs for each material.

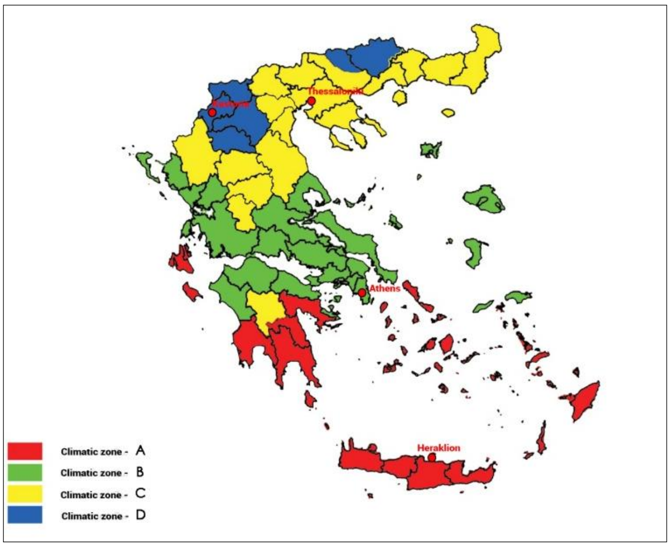

Figure 5.1: Climatic zones of Greece [T.O.T.E.E. 20701-1/2010]

5.1.1 Model description

For the simulation process the dynamic thermal behaviour of a test cell model was examined (figure 5.2). The test cell is a dwelling model of 110.15 m^2 floor area that consists of a frame made of reinforced concrete, four walls, a floor and a ceiling. On the south side of the model a window and an overhang is placed. The walls were constructed from the tested materials and they were insulated externally. For each simulation run, a different material was selected. However the total thermal transmittance (U-value) of the wall remained constant. The properties and thicknesses of the materials in each case are shown it Table 5.2. The roof and the walls are adjacent to external air, while the floor is adjacent to the ground.

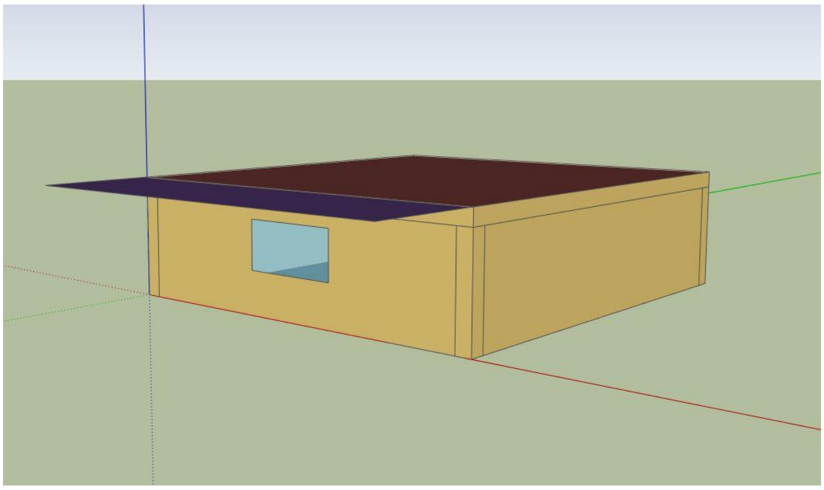

Figure 5.2: Test cell model

The energy simulation software used for this study is EnergyPlus. EnergyPlus is a dynamic building energy analysis and thermal load simulation program, developed by the US Department of Energy (DoE) [http://apps1.eere.energy.gov/buildings /energyplus]

As the scope of this study is to compare the performance of thermal mass materials in terms of energy savings, a simplified test cell model was selected, instead of the simulation of a whole building. For the same reason HVAC systems were not simulated. Therefore, the energy required for the operation of HVAC systems will not be included to the simulation results.

5.1.2 Fixed parameters

The following fixed parameters were implemented in every simulation test:

- Run period : annual
- Thermal zones: one
- Model use : residential
- Floor area: 10 x 11.15 = 110.15 m^2
- Height : 3.0 m
- Total wall area : 124.78 m^2
- Window area : 2.4 x 1.2 = 2.80 m^2
- Overhang length : 3.0 m
- Window and overhang orientation : South
- Occupant density: 5 people per 100 m^2
- Ventilation rate : 75 m^3/h

- Lighting heat gain: 6.4 W/m^2
- Occupant sensible heat gain: 4 W/m^2
- Equipment sensible heat gain : 2 W/m^2
- Air-tightness : 17.9 m^3/h

The frame elements were constructed from reinforced concrete and they were insulated externally. Their thickness was always constant and it is shown in Table 5.1. The fixed U-values of the opaque elements and of the window are shown in Table 5.1. These values are obtained from the requirements of KENAK in climatic zone D. The requirements are U< 0.4 for walls, U< 0.35 for floors adjacent to the ground, U< 0.35 for roofs and U<2.60 for windows

Table 5.1: U-values of the building elements

Building element	U-value (W/m^2K)
Exterior wall	0.36
RC elements	0.37
Floor	0.56
Roof	0.30
Window	2.60

5.1.3 Properties of construction elements

The following table presents the structure of the construction elements used for simulation tests. The values for density (ρ), specific heat (Cρ) and thermal conductivity (λ) are taken from the Technical Guidelines (TOTEE 20701-2/2010), while thermal diffusivity (α) and periodic penetration depth (d_p) were calculated using those values.

Table 5.2: Layers and properties of the construction elements

Layers (from inside)	d (m)	ρ (kg/m³)	Cρ (J/kg/K)	λ λ (W/m/K)	α (Ws$^{1/2}$/m^{2}K)	d_p (m)
			W1 (brick wall) d= 35cm			
Plaster	0.02	1800	1000	0.87	4.8E-07	0.12
Common brick	0.24	1500	1000	0.51	3.4E-07	0.10
Insulation	0.07	35	1450	0.033	6.5E-07	0.13
Plaster	0.02	1800	1000	0.87	4.8E-07	0.12
			W2 (limestone) d= 32cm			
Limestone	0.2	2200	1000	1.7	7.7E-07	0.15
Insulation	0.08	35	1450	0.032	6.3E-07	0.13
Limestone	0.04	2200	1000	1.7	7.7E-07	0.15
			W3 (concrete blocks) d= 31cm			
Plaster	0.02	1800	1000	0.87	4.8E-07	0.12
Lightweight concrete	0.2	2000	1100	1.1	5.0E-07	0.12
Insulation	0.08	35	1450	0.033	6.5E-07	0.13
Plaster	0.01	1800	1000	0.87	4.8E-07	0.12
			W4 (AAC blocks) d=33cm			
Plaster	0.02	1800	1000	0.87	4.8E-07	0.12
AAC	0.25	800	1000	0.22	2.8E-07	0.09
Insulation	0.05	35	1450	0.034	6.7E-07	0.14
Plaster	0.01	1800	1000	0.87	4.8E-07	0.12
			Frame elements (RC beams,columns) d=36cm			
Plaster	0.02	1800	1000	0.87	4.8E-07	0.12
Reinforced concrete	0.25	2400	1000	2.5	1.0E-06	0.17
Insulation	0.08	35	1450	0.033	6.5E-07	0.13
Plaster	0.01	1800	1000	0.87	4.8E-07	0.12
			Roof d= 30cm			
Reinforced concrete	0.2	2400	1000	2.5	1.0E-06	0.17
Insulation	0.1	35	1450	0.033	6.5E-07	0.13
			Floor d= 32cm			
Reinforced concrete	0.2	2400	1000	2.5	1.0E-06	0.17
Insulation	0.05	35	1450	0.033	6.5E-07	0.13

The following tables present the thermal mass properties of the exterior walls and frame elements which are used in simulation tests. The values of decrement factor (F_α), time lag (Φ), surface heat capacity (k), thermal transmittance (Y) as well as the following thermal transmittance charts, were calculated using the Thermal Properties Calculator, which is provided by the Concrete Centre website [www.concretecentre.com]

Table 5.3: Thermal mass properties of the construction elements

d (m)	U -value (W/m^2K)	Decrement factor F_α (m)	Time lag (ϕ) (h)	k-value (kJ/m^2K)	Y-value W/m^2K
			W1 (brick wall)		
0.35	0.36	0.09	12.48	156	4.42
			W2 (limestone)		
0.32	0.36	0.17	9.07	220	5.84
			W3 (concrete blocks)		
0.31	0.36	0.13	9.67	212	5.10
			W4 (AAC blocks)		
0.33	0.36	0.11	12.94	100	3.65
			Frame elements (RC beams,columns)		
0.36	0.37	0.12	9.03	228	5.57

5.1.4 Internal thermal mass

The influence of internal thermal mass in the thermal behaviour of the test cell was examined, by the addition of interior walls. In this case the thickness of the wall remained constant at 10cm. The interior walls were constructed by the same material as the exterior walls and their total surface is $30m^2$. In order to have a clearest view of the performance of each material itself, no plaster or coating was used.

5.1.5 Simple pre-cooling

The potential of using the thermal mass for energy storage in order to overcome the mismatch barrier between supply and demand in a NZEB was investigated. A simple pre-cooling strategy was adopted and implemented in the test cell. During the summer months the model was pre-cooled at 23^oC between 9am and 15pm. During the rest hours of the day the thermostat was turned off. The effect of this strategy on energy savings and in thermal comfort was analyzed.

The above cooling strategy could be used from a NZEB with a solar combisystem. This building could exploit the high irradiation of the summer in order to cover its needs for cooling on-site. As it is shown on figures 5.3a and 5.3b the maximum direct normal irradiance for all the studied cities, occurs between 9am and 15pm.

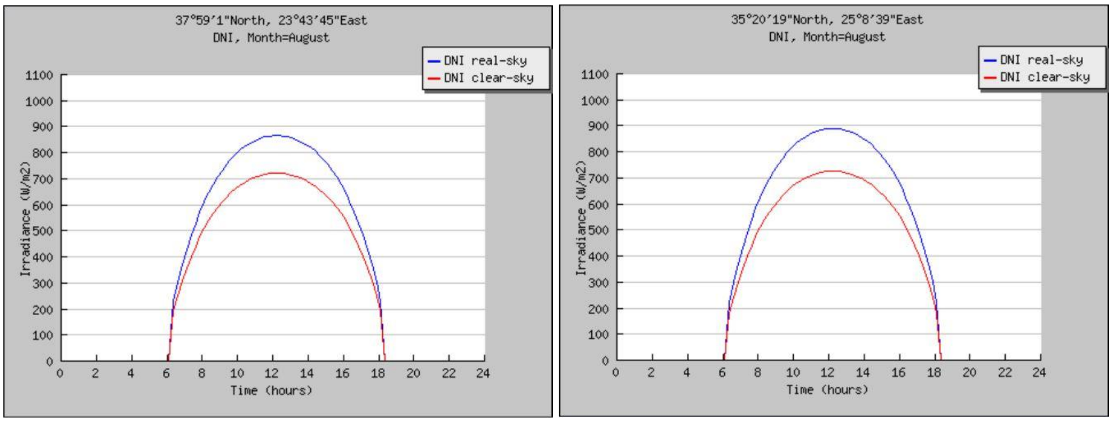

Figure 5.3a: Direct normal irradiance and clear-sky direct normal irradiance in August for Athens and Heraklion [http://re.jrc.ec.europa.eu/pvgis/]

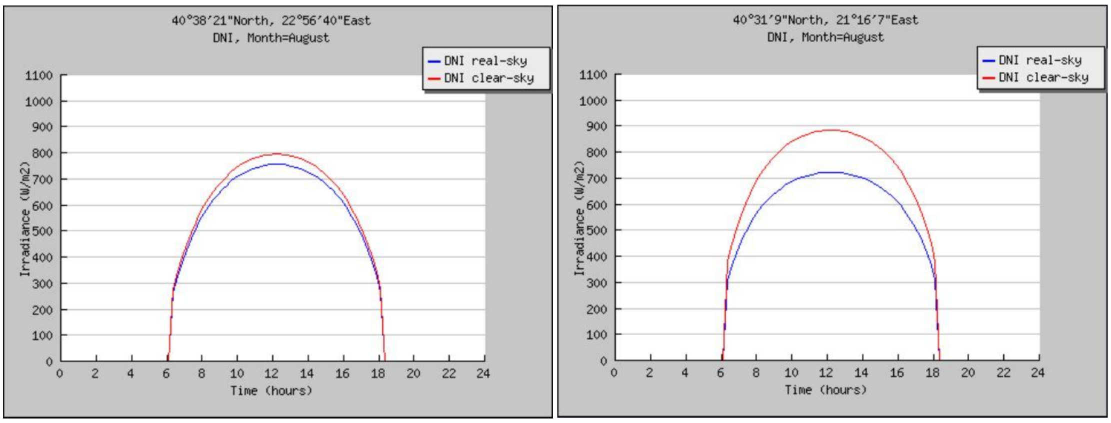

Figure 5.3b: Direct normal irradiance and clear-sky direct normal irradiance in August for Thessaloniki and Kastoria [http://re.jrc.ec.europa.eu/pvgis/]

5.2 Simulation results

5.2.1 Case 1: Comparison of brick wall with walls made of the selected thermal mass materials

The following tables present simulation results of case 1. W1 stands for brick wall, W2 for the wall made of limestone, W3 for the concrete wall and W4 for the AAC wall. Each wall is compared with the reference brick wall. Negative values mean increased thermal loads.

Table 5.4 : Annual space heating and cooling demand for Heraklion (Zone A)

Wall	Heating Loads (kWh)	Energy Savings		Cooling Loads (kWh)	Energy Savings		Net Savings(%)
		kWh	%		kWh	%	
W1 (ref)	110.15	-	-	2334.92	-	-	-
W2	104.81	5.34	4.8	2354.81	-19.89	-0.9	-0.60
W3	108.89	1.26	1.1	2320.02	14.9	0.6	0.66
W4	117.47	-7.32	-6.6	2334.01	0.91	0.0	-0.26

Table 5.5 : Annual space heating and cooling demand for Athens (Zone B)

Wall	Heating Loads (kWh)	Energy Savings		Cooling Loads (kWh)	Energy Savings		Net Savings(%)
		kWh	%		kWh	%	
W1 (ref)	877.51	-	-	2094.79	-	-	-
W2	868.95	8.56	1.0	2117.80	-23.01	-1.1	-0.49
W3	876.13	1.38	0.2	2085.18	9.61	0.5	0.37
W4	883.55	-6.04	-0.7	2096.64	-1.85	-0.1	-0.27

Table 5.6 : Annual space heating and cooling demand for Thessaloniki (Zone C)

Wall	Heating Loads (kWh)	Energy Savings		Cooling Loads (kWh)	Energy Savings		Net Savings(%)
		kWh	%		kWh	%	
W1 (ref)	1961.37	-	-	1479.06	-	-	-
W2	1942.44	18.93	1.0	1493.09	-14.03	-0.9	0.14
W3	1960.91	0.46	0.0	1469.78	9.28	0.6	0.28
W4	1969.15	-7.78	-0.4	1482.57	-3.51	-0.2	-0.33

Table 5.7 : Annual space heating and cooling demand for Kastoria (Zone D)

Wall	Heating Loads (kWh)	Energy Savings		Cooling Loads (kWh)	Energy Savings		Net Savings(%)
		kWh	%		kWh	%	
W1 (ref)	2949.83	-	-	798.7	-	-	-
W2	2910.63	39.2	1.3	814.69	-15.99	-2.0	0.62
W3	2958.65	-8.82	-0.3	783.68	15.02	1.9	0.17
W4	2970.86	-21.03	-0.7	799.8	0.9	0.1	-0.54

5.2.2 Case 2 - Internal mass addition

The following tables present simulation results of case 2 (internal thermal mass addition). Each model is compared with the corresponding model of the same material from case 1. Columns 2 and 4 show the percentage of the increased demand due to the addition of thermal mass.

Table 5.8 : Annual space heating and cooling demand of test cell model with addition of interior walls for Heraklion (Zone A)

Wall	Heating Loads (kWh)	Heating demand (%)	Cooling Loads (kWh)	Cooling demand (%)
W1	111.32	1.05	2364.25	1.24
W2	105.35	0.51	2385.51	1.29
W3	109.52	0.58	2348.17	1.20
W4	119.30	1.53	2366.85	1.31

Table 5.9 : Annual space heating and cooling demand of test cell model with addition of interior walls for Athens (Zone B)

Wall	Heating Loads (kWh)	Heating demand (%)	Cooling Loads (kWh)	Cooling demand (%)
W1	890.64	1.47	2120.9	1.23
W2	881.28	1.40	2141.18	1.09
W3	888.59	1.40	2109.06	1.13
W4	897.24	1.53	2122.78	1.23

Table 5.10 : Annual space heating and cooling demand of test cell model with addition of interior walls for Thessaloniki (Zone C)

Wall	Heating Loads (kWh)	Heating demand (%)	Cooling Loads (kWh)	Cooling demand (%)
W1	1968.44	0.36	1498.56	1.30
W2	1951.16	0.45	1511.86	1.24
W3	1986.03	1.26	1486.64	1.13
W4	1995.31	1.31	1501.17	1.24

Table 5.11 : Annual space heating and cooling demand of test cell model with addition of interior walls for Kastoria (Zone D)

Wall	Heating Loads (kWh)	Heating demand (%)	Cooling Loads (kWh)	Cooling demand (%)
W1	2984.08	1.15	805.63	0.86
W2	2943.58	1.12	823.74	1.10
W3	2992.18	1.50	791.5	0.99
W4	3005.90	1.17	806.5	0.83

5.2.3 Case 3 - Pre-cooling during summer months

The following tables present simulation results of case 3 (simple pre-cooling during summer months). Each model is compared with the corresponding model of the same material from case 2. In the second column the percentage of the increased demand due to pre-cooling is shown.

Table 5.13 : Annual space cooling demand of test cell model after pre-cooling during summer months for Heraklion (Zone A)

Wall	Cooling Loads (kWh)	Cooling demand (%)
W1	2364.25	1.24
W2	2385.51	1.29
W3	2348.17	1.20
W4	2366.85	1.31

Table 5.14 : Annual space cooling demand of test cell model after pre-cooling during summer months for Athens (Zone B)

Wall	Cooling Loads (kWh)	Cooling demand (%)
W1	2120.9	1.23
W2	2141.18	1.09
W3	2109.06	1.13
W4	2122.78	1.23

Table 5.15 : Annual space cooling demand of test cell model after pre-cooling during summer months for Thessaloniki (Zone C)

Wall	Cooling Loads (kWh)	Cooling demand (%)
W1	1498.56	1.30
W2	1511.86	1.24
W3	1682.86	1.13
W4	1528.23	1.24

Table 5.16 : Annual space cooling demand of test cell model after pre-cooling during summer months for Kastoria (Zone D)

Wall	Cooling Loads (kWh)	Cooling demand (%)
W1	805.63	0.86
W2	823.74	1.10
W3	791.5	0.99
W4	806.5	0.83

5.3 Discussion of simulation results

The dynamic thermal behaviour of a test cell model was simulated under the climatic conditions of the four climatic zones of Greece. The exterior walls were constructed from the tested materials (limestone, concrete, AAC) and they were insulated externally. For each simulation test, a different material was selected, keeping the total thermal transmittance of the wall constant. The results of the simulation tests showed that:

The climate conditions affect significantly the building's energy demand. Exterior walls made from the same materials with the same U-values and same thicknesses have different energy performance in different locations.

In any case the use of a thermal mass material other than brick for exterior wall construction, does not lead to significant alterations of the energy demand of a building. This holds true for the usual wall thickness that can be found in Greece. The alterations in energy demand of the test cell models never exceeded 1% annually.

The choice of the thermal mass material does not play such an important role in the energy demand of the building. It seems that the overall structure of the exterior walls is the one that defines the thermal behaviour of the building. The influence of the parameters that have a non steady-state effect, such as thermal admittance, time lag, surface heat capacity etc., is greater than the influence of the material's properties itself.

The fact that the material itself does not affect significantly the energy demand of a building is also shown by the internal thermal mass tests. In this case the thermal performance of single-layered interior walls was simulated. The results showed that the thermal performance of each material was almost the same. In any case the addition of internal thermal mass led to an increase in energy consumption, which was proportional to the total surface of the internal thermal mass. However, simulations tests showed that this increase is considered to be low.

Since the choice of the thermal mass material does not play a significant role in the energy demand of the building, the choice of the material with the lowest cost could be more important. In this case, the use of AAC blocks for the construction of walls is the most advantageous. Although AAC is supposed to be a material with low heat storage ability, the simulation tests showed that the increase in energy demand by the use of AAC blocks instead of common bricks is below 1% annually.

The use of thermal mass for energy storage in order to overcome the mismatch barrier between supply and demand in a NZEB by implementing a simple pre-cooling strategy during the summer months is not recommended. Simulation tests showed that in any case this strategy leads to increased energy consumption. Moreover, this strategy affects negatively the thermal comfort, as the internal temperature exceeded the 26^{o}C limit for a significant period of time.

Table 5.17: Thermal mass properties of the brick wall

W1 (brick wall)					
d (m)	U -value (W/m^2K)	F_α (m)	Time lag (ϕ) (h)	k-value (kJ/m^2K)	Y-value (W/m^2K)
0.35	0.36	0.09	12.48	156	4.42

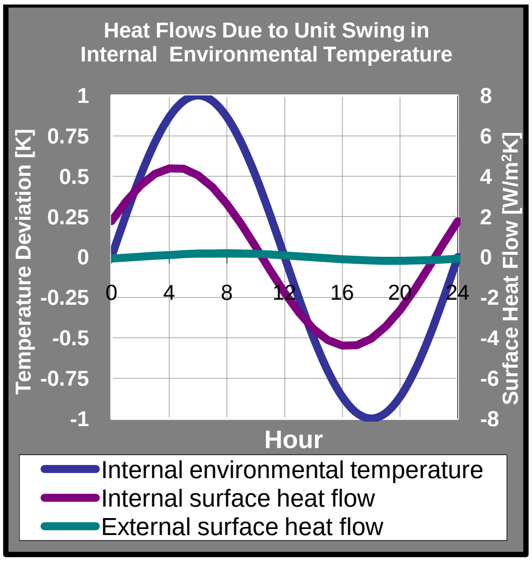

Figure 5.4: Thermal Admittance graph for brick wall

Table 5.18: Thermal mass properties of the wall made of limestone

W2 (limestone)					
d (m)	U -value (W/m^2K)	F_α (m)	Time lag (ϕ) (h)	k-value (kJ/m^2K)	Y-value (W/m^2K)
0.32	0.36	0.17	9.07	220	5.84

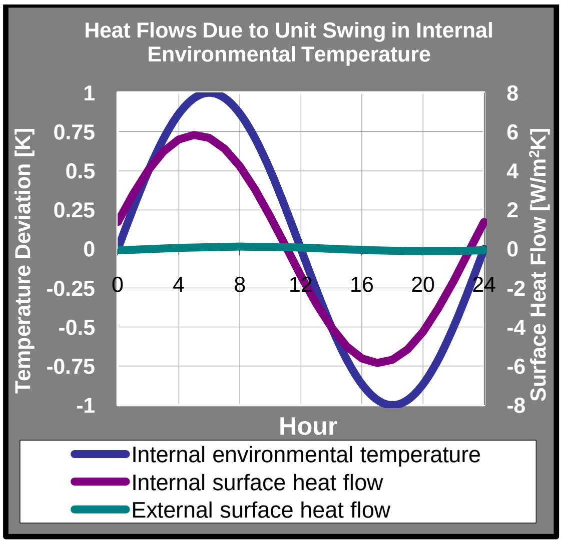

Figure 5.5: Thermal Admittance graph for limestone wall

Table 5.17: Thermal mass properties of the brick wall

W1 (brick wall)					
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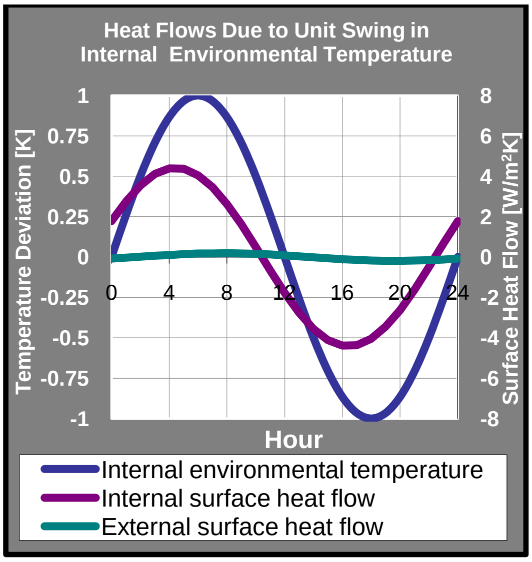

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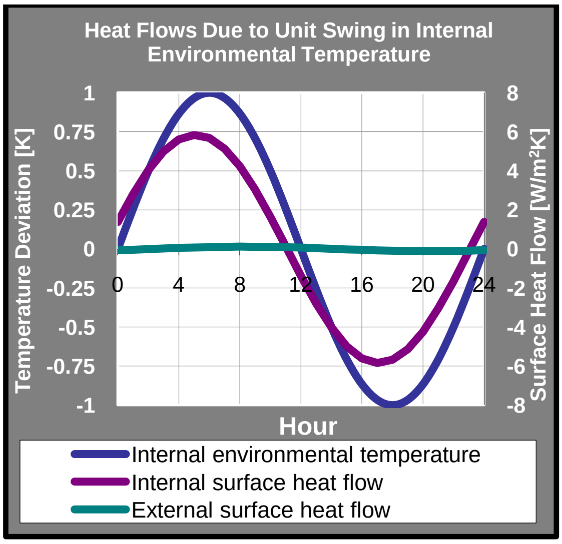

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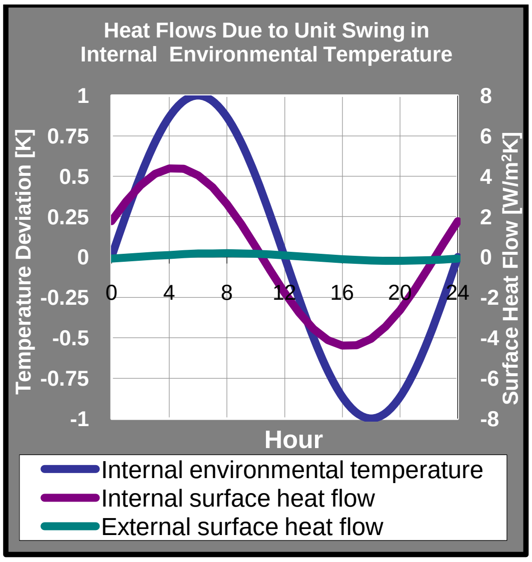
Table 5.17: Thermal mass properties of the brick wall

W1 (brick wall)					
d	U -value	F_{α}	Time lag (ϕ)	k-value	Y-value
(m)	(W/m^2K)	(m)	(h)	(kJ/m^2K)	(W/m^2K)
0.35	0.36	0.09	12.48	156	4.42



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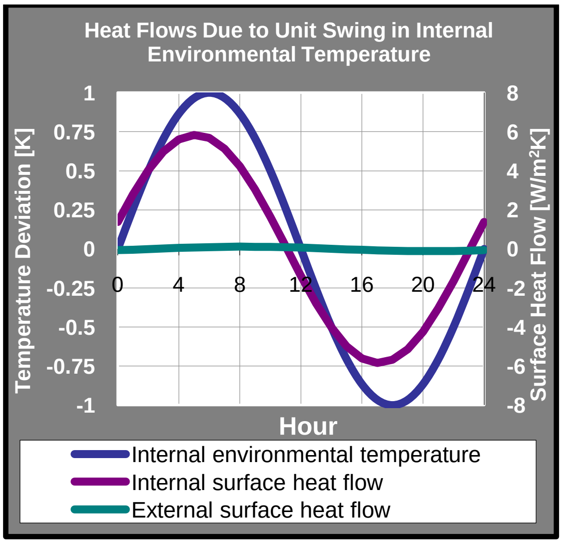

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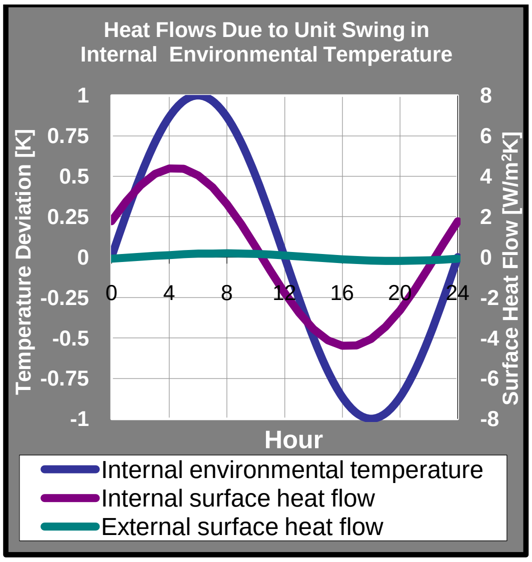

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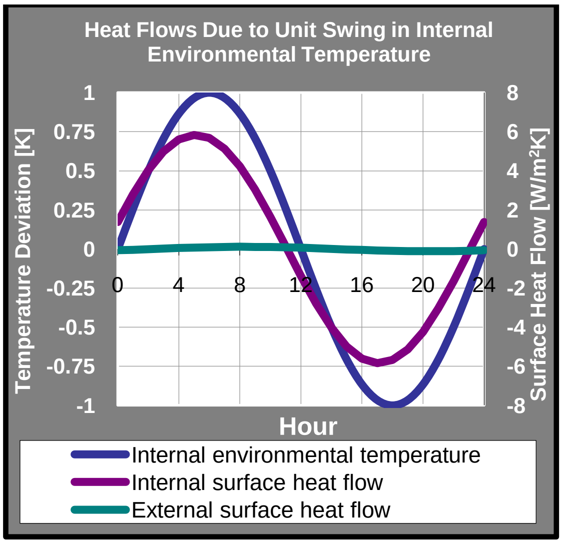

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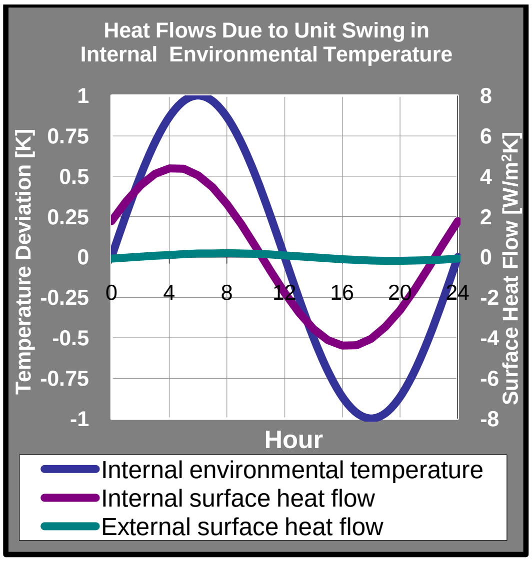

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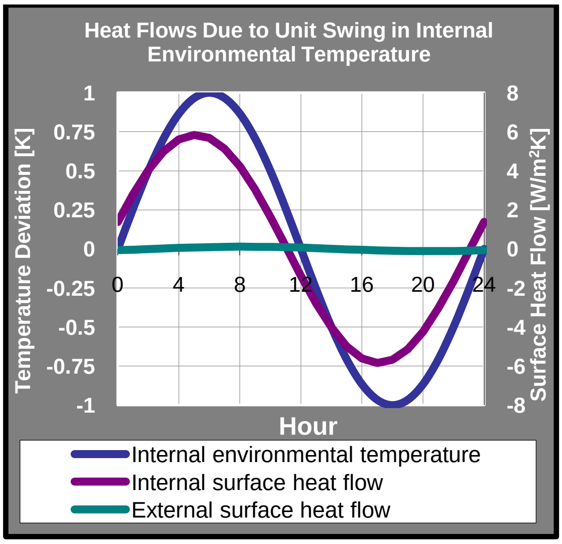

Figure 5.5: Thermal Admittance graph for limestone wall

6 Conclusions and perspectives

6.1 Conclusions regarding thermal mass materials selection

- During the selection process 127 different materials both conventional and unconventional were checked. The attempt to discover new unconventional materials suitable for periodic thermal energy storage did not lead to impressive findings. None of the alternative materials managed to clearly stand out against the conventional ones.

Based on the materials' thermophysical properties and setting the objectives of maximum thermal energy storage, minimum embodied energy and minimum cost, three materials stood out through the selection process:

- Limestone is the best material for periodic thermal energy storage in buildings as it combines excellent storage ability (max effusivity) and simultaneously the lowest embodied energy.

- Autoclaved Aerated Concrete (AAC) on the other hand, is the cheapest material that can be used for efficient periodic thermal energy storage in buildings.

- Concrete and especially lightweight concrete recorded an excellent performance in all three objectives that were set, proving that it is the material that combines high storage ability, low embodied energy and low cost.

6.2 Conclusions from the simulation tests

The dynamic thermal behaviour of a test cell model was simulated under the climatic conditions of the four climatic zones of Greece. The exterior walls were constructed from the tested materials (limestone, concrete, AAC) and they were insulated externally. For each simulation test, a different material was selected, keeping the total thermal transmittance of the wall constant. The results of the simulation tests showed that:

- The climate conditions affect significantly the building's energy demand. Exterior walls made from the same materials with the same U-values and same thicknesses have different energy performance in different locations.

- In any case the use of a thermal mass material other than brick for exterior wall construction, does not lead to significant alterations of the energy demand of a building. This holds true for the usual wall thickness that can be found in Greece. The alterations in energy demand of the test cell models never exceeded 1% annually.

- The choice of the thermal mass material does not play such an important role in the energy demand of the building. It seems that the overall structure of the exterior walls is the one that defines the thermal behaviour of the building. The influence of the parameters that have a non steady-state effect, such as thermal admittance, time lag, surface heat capacity etc., is greater than the influence of the material's properties itself.

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- The use of thermal mass for energy storage in order to overcome the mismatch barrier between supply and demand in a NZEB by implementing a simple pre-cooling strategy during the summer months is not recommended. Simulation tests showed that in any case this strategy leads to increased energy consumption. Moreover, this strategy affects negatively the thermal comfort, as the internal temperature exceeded the 26^{o}C limit for a significant period of time.

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